A PETROLOGICAL INVESTIGATION OF THE XENOLITHIC ULTRABASIC DYKES OF THE CUILLINS AND THE STRATHAIRD PENINSULA, ISLE OF SKYE

Fergus George Ferguson Gibb

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University of St Andrews

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Frontispiece.

A xenolithic ultrabasic dyke cutting an earlier xenolithic ultrabasic dyke in Coire a' Ghreadaidh.

PREFACE

Academic Career

The candidate was educated at Dundee High School and first matriculated in the University of St. Andrews in October, 1959. In June 1963 he graduated B.Sc. with Second Class Honours in Geology. In August of the same year he enrolled as a research student in the University of St. Andrews to study the petrology of ultrabasic igneous minor intrusions under the supervision of Dr. H.I. Drever, and the results of his research are embodied in this thesis.

Certificate of Originality

I certify that this thesis is my own composition and is based on research carried out by me in the Department of Geology, University of St. Andrews between 1963 and 1966. It has not been previously submitted to another university or for a higher degree.

Fergus G. F. Gibb.

Supervisor's Certificate

I certify that Fergus George Ferguson Gibb has pursued a course of research under my supervision and has fulfilled the requirements of Ordinance 16 (University of St. Andrews). He is qualified to submit this thesis in application for the degree of Doctor of Philosophy.

Dr. H. I. Drever.

ABSTRACT.

The Tertiary ultrabasic dykes of the Cuillins and the Strathaird peninsula are studied and classified on the bases of their content of cognate xenoliths and textures. Two principal types are recognised, the Coire Lagan type (similar to those studied by Drever and Johnston, 1958) and the xenolithic Ben Cleat type. The dykes of the Ben Cleat type are investigated in detail.

The Ben Cleat dykes are composed principally of olivine (Fa_{11}), plagioclase (An_{84} with normally zoned margins) and clinopyroxene (Ca_{43} Mg_{46} Fe_{11}) with accessory chrome spinel: the compositions of these minerals are constant throughout the dykes.

The transverse variations in modal amount and crystal size of the three principal minerals within selected representative dykes have been determined and it is established beyond doubt that the dykes are differentiated. The petrogenetic hypothesis of composite intrusion previously proposed for these dykes by Bowen (1928) is examined in the light of this evidence and found to be inadequate. It is suggested that the dykes were intruded as suspensions of olivine crystals and rock fragments in an ultrabasic liquid from which plagioclase, pyroxene and a small amount of olivine subsequently crystallized.

It is demonstrated that the dykes are unlikely to have been differentiated in their present positions and the possibility that the

differentiation occurred during their emplacement is examined. The processes by which crystals might migrate in flowing magma are considered, and it is shown that the mineral distributions and crystal size variations occurring in the dykes are analogous to those expected, from the results of theoretical and experimental investigations, to arise during laminar flow of suspensions of solid particles in a viscous fluid in vertical conduits. Several of the apparently anomalous differentiation phenomena are also interpreted in the light of theoretical fluid mechanics as the results of flow in near-vertical fissures. It is concluded that - (i) the dykes were each intruded as a single pulse of ultrabasic liquid containing large amounts of olivine phenocrysts, (ii) the distinctive type of differentiation which is characteristic of these dykes occurred during their intrusion and (iii) the mechanism involved was flowage differentiation.

The petrographies of the cognate xenoliths are studied and their distribution and orientation explained on the basis of laminar flow of the dyke magma.

The age of the xenolithic ultrabasic dykes in relation to the other intrusions of the Cuillin Tertiary igneous complex is reconsidered and it is suggested that the dykes were emplaced contemporaneously with the Sgurr Dubh ultrabasic intrusion.

Petrogenetic hypotheses are advanced for both the dykes and the cognate xenoliths and it is tentatively proposed that both were derived by partial fusion of a deep-seated peridotitic rock.

CONTENTS

I. INTRODUCTION

1. THE AREAS INVESTIGATED.

Although ultrabasic minor intrusions of Tertiary age occur throughout Skye and the neighbouring islands, the xenolithic ultrabasic dykes with which this work is primarily concerned appear to be confined to two adjacent, but geographically distinct, areas of south-west Skye, namely the Strathaird peninsula and the Cuillins.

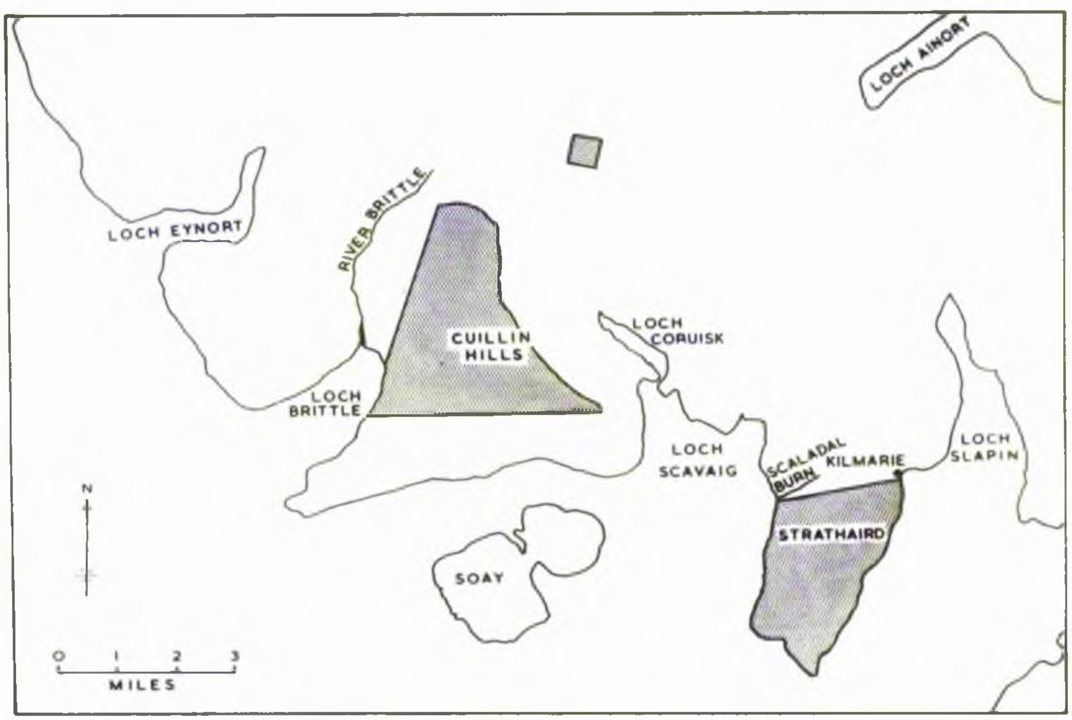

Fig. 1. Areas in which ultrabasic dykes have been investigated.

The Strathaird peninsula, lying between Loch Scavaig and Loch Slapin, extends southwards for seven miles from the head of the latter. The present research is restricted to the part of the peninsula which lies to the south of a line joining Kilmarie and the mouth of the Scaladal burn (Fig. 1) and throughout this thesis the term "Strathaird peninsula" refers only to this area unless otherwise indicated.

The southern and eastern parts of the peninsula are composed of relatively flat-lying Mesozoic sediments which form low rounded hills and coastal cliffs frequently over 100 feet high. The north-western part of the area is composed of sub-horizontal flows of basalt overlying the sediments. Several thick basic sills have been intruded into both sediments and lavas and subsequent erosion has produced relatively high, flat-topped hills with steep cliff faces. Ben Meabost (1128 feet) and Ben Cleat (850 feet) (Fig. 4) are hills of this type. Along the coast exposure is excellent but inland the bedrock is mantled by a thick layer of glacial drift, peat and vegetation, and outcrops are restricted to the beds of some of the larger streams.

The Cuillins, lying between Glen Sligachan and Glen Brittle, are the highest mountains in Skye and cover an area of more than thirty square miles. Xenolithic ultrabasic dykes, however, appear to occur only in the southern and western parts of the Cuillin area and in a small area near the northern edge of the mountains. Consequently, only these areas have been investigated in detail in the course of the present research (Fig. 1).

In the Cuillin area a basic/ultrabasic plutonic igneous complex of Tertiary age intrudes earlier Tertiary basaltic lavas. The lavas form the lower ground bordering the mountains which are formed mainly of gabbros and eucrites. Post-Tertiary erosion, especially Quaternary glaciation, has produced one of the most rugged and picturesque skylines in Britain with many peaks over 3000 feet high. On the lower ground around the mountains exposure is generally poor, but in the corries, where there are frequently vast glaciated slabs of rock, and along the ridges, it is often complete. At the bases of most of the steeper faces, however, huge screes obscure much of the geology.

2. PREVIOUS WORK.

The presence of ultrabasic intrusions among the gabbros and basaltic lavas of south-west Skye was first recorded by Harker (1904) in his classic memoir on the Tertiary igneous rocks of the island. He distinguished two groups of ultrabasic intrusions, each having plutonic and hypabyssal members, referring to them as "earlier" and "later peridotites".

According to Harker the "early peridotites" were predominantly plutonic but, apart from the "arcuate laccolite of Sgurr Dubh", the intrusions were relatively small. [Two of them have since been described as sills (Weedon, 1960).] To this period of intrusion he ascribed only a few dykes, all of which were in the Cuillins and were believed by him to be feeders of the laccolites.

Harker's "later peridotites" consisted of the "peridotite dykes of the Cuillins and of the Strathaird peninsula", the "peridotite sills" of Soay and the "picrite boss of An Sguman". He believed that the "earlier peridotites" represented the initial phase of plutonic intrusion in Skye and that the "later peridotites" were among the youngest igneous rocks in the area; i.e. that the two groups of ultrabasic intrusions, although closely associated spatially, were at opposite ends of the intrusive sequence. Although he presented brief petrographical descriptions of a number of the "later peridotite" dykes and noted that many of the larger examples tended to contain ultrabasic xenoliths, Harker advanced no petrogenetic hypothesis.

Bowen (1928) re-investigated some of the ultrabasic dykes of the Cuillins and observed that :-

i) the central parts of the dykes contained more olivine than the margins,

ii) offshoots from the dykes were generally of a doleritic nature and

iii) there were considerable local variations within individual dykes.

He also described several small ultrabasic dykes from Coire Lagan and added these to Harker's "later peridotites" (Bowen, 1928, p. 156-7). He noted the difference in olivine content between these and Harker's larger dykes and mainly on this basis suggested that the amount of olivine in a dyke was directly proportional to its width.

As a result of his observations, Bowen concluded that the ultrabasic dykes of the Cuillins were composite intrusions.

In their review of Hebridean picritic minor intrusions Drever and Johnston (1958, p. 464) observed that "the small dykes, ..., exhibit important differences from the larger and often xenolithic types". Having established this division they studied the smaller dykes, including those from Coire Lagan described by Bowen, in considerable detail. [Dykes of this type are referred to as the Coire Lagan type by the present writer.] Unlike Bowen, they did not favour composite intrusion but considered that the small dykes were each emplaced as a single pulse of "eucritic" magma containing variable amounts of phenocrystic olivine.

Weedon (1960) regarded the two small "earlier peridotite laccolites" on the southern flank of Gars-bheinn as sills and noted certain chemical affinities between the lower or Gars-bheinn sill and one of the ultrabasic dykes described by Harker and Bowen.

From the lower part of Coir' a' Ghrunnda, Robertson (1963) described fourteen ultrabasic dykes, twelve of which were similar to those described by Drever and Johnston, i.e. of the Coire Lagan type. He noted that the remaining two dykes, which were larger (and contained cognate xenoliths), exhibited certain similarities to the Sgurr Dubh intrusion.

Wyllie and Drever (1963) described in detail one of the ultrabasic sills of Soay which, in the present writer's opinion, is essentially similar to the Coire Lagan type of dyke, and Weedon (1965) has recently published an account of the Sgurr Dubh ultrabasic intrusion.

In addition to the principal works on ultrabasic rocks in south-west Skye listed above, reference is made to other works on the igneous rocks of Skye at the appropriate points throughout this thesis.

3. THE PRESENT RESEARCH.

The present research is a re-investigation of the ultrabasic minor intrusions of south-west Skye, particularly those containing cognate xenoliths. When definitely identified as such in the field, dykes of the Coire Lagan type were not examined in detail since intrusions of this type have been extensively studied by Drever and Johnston (1958).

The majority of the dykes investigated are of the xenolithic or Ben Cleat type (see chapter IV) and the greater part of this thesis is devoted to a detailed study of this type of dyke. The principal aims of the present research into the Ben Cleat type of ultrabasic dyke may be summarized as follows :-

i) to determine the nature of the dykes and cognate xenoliths,

ii) to determine the intrusive mechanics of the dykes,

iii) to establish the age relationship between the dykes and the rest of the Cuillin igneous complex, and

iv) to determine the origins of the dykes and cognate xenoliths.

By attempting to achieve these aims the writer hopes to contribute towards a fuller understanding of ultrabasic minor intrusions.

The remainder of the dykes investigated are either of the Coire Lagan type or of uncertain type. Some of these which are of considerable petrological interest are briefly described (chapter XX).

II. NOMENCLATURE

Harker (1904, p. 377) referred to the ultrabasic dykes of south-west Skye as peridotites but he did so "under protest" as this term did not distinguish the dykes from their plutonic equivalents. Many of the dyke rocks, however, have textures and grain-sizes identical with those of plutonic rocks and a distinction between two otherwise identical rocks based solely on their modes of occurrence would appear to be an unnecessary complication.

Drever and Johnston (1958, p. 464) described the Coire Lagan dykes as picritic, using the term (p. 469) "to denote in minor intrusions and lavas, an amount of forsteritic olivine considerably beyond that which normally crystallizes in basaltic magma" : this amount they defined more specifically as varying "between 25 and 60%".

Specimens obtained in the course of the present research range from an almost pure olivine rock to one composed essentially of plagioclase and clinopyroxene. This variation is obviously beyond the scope of any single rock name and the terms dunite, peridotite, felspathic peridotite, picrite, allivalite and olivine-eucrite are all employed to cover the range of rock types occurring in the dykes and as cognate xenoliths. These terms are reviewed below and defined in the sense in which they are used in this thesis.

The dyke rocks and cognate xenoliths are composed of varying amounts of forsteritic olivine, clinopyroxene and bytownite with accessory and secondary minerals, and the different rock types are established on the relative amounts of the three main minerals. In no case is texture, grain-size or mode of occurrence implied by the rock name.

Dunite was defined by Johannsen (1938, iv, p. 405) as a rock composed "essentially of olivine" which in transition towards "gabbros" may contain a little basic plagioclase. Smith (1962, p. 5) stated that the composition of dunite was "dominantly olivine, with only minor amounts of pyroxene, plagioclase and spinel". In this thesis Smith's definition is used with the additional stipulation that olivine must exceed 90% (by volume) of the rock.

Peridotite has been used to denote a wide variety of rocks by different writers. The term was introduced by Cordier (1868, p. 118) for a rock composed mainly of labradorite, olivine and augite. Rosenbusch (1877, p. 522), however, employed peridotite to denote olivine-bearing rocks which were free from plagioclase. Harker (1904, p. 68-69) used the term "in a broad sense" to include "picrites" (see below) and "typical peridotites in which the characteristic mineral occurs almost to the exclusion of all others". Johannsen (1938, iv, p. 404) proposed that the name peridotite should be used for a rock composed of pyroxene and olivine with less than 50% of the latter. [For rocks in which olivine was dominant he preferred the name olivinite.] Brown (1956, p. 12) defined peridotite as containing olivine, plagioclase and augite with more olivine than plagioclase, whereas Moorhouse (1959, p. 313) considers it to be "an ultrabasic rock containing over 30% olivine and less than 10% leucocratic minerals. Smith (1962, p. 7) stated :- "peridotite is a variant of dunite that contains more than 10% pyroxene" with "accessory plagioclase". With the exception of Johannsen all the above writers have considered olivine to be the dominant mineral and, consequently, the name peridotite is used by the present writer to signify a rock containing between 50 and 90% olivine. In view of the principal uses of the term in the past to denote an olivine/pyroxene rock rich in plagioclase on the one hand (Cordier, Harker, Brown) and free from or poor in plagioclase on the other (Rosenbusch, Johannsen, Moorhouse, Smith) the writer proposes that the terms peridotite and felspathic peridotite be used for rocks in which the pyroxene:plagioclase ratios are respectively greater and less than unity (Fig. 2).

Picrite was used by Harker to denote rocks composed principally of olivine but "in which augite and felspar are fairly well represented". Drever and Johnston (1958, p. 459-460) reviewed the term and concluded that the adjective picritic was preferable to picrite (see above) but in a later paper (1965, p. 197) adopted the name picrite for rocks containing more than 40% olivine and the prefix picro- for those with 20-40% olivine. Smith (1962, p. 7) defined picrite as containing olivine (20-50%), plagioclase (15-30%), orthopyroxene and clinopyroxene. The term picrite is employed in this thesis to signify a rock composed of 20-50% olivine (cf. Smith) and more than 10% each of plagioclase and augitic clinopyroxene (cf. Harker; Drever and Johnston).

Allivalite was introduced by Harker (1908, p. 70-71) to describe anorthite-olivine rocks from Rhum "in which the two minerals are in approximately equal amount or the felspar preponderates". Brown (1956, p. 12) pointed out that the plagioclase in these rocks was not anorthite "in the modern sense" but calcic bytownite. He recommended that allivalite be confined to rocks of this type with plagioclase more calcic than An_{80} and that the term troctolite be extended to cover similar rocks with plagioclase in the range An_{50}-An_{80}. A modification of Harker's original definition is adopted here, the name allivalite being used for rocks composed of up to 90% plagioclase (more calcic than An_{70}) with less than 50% olivine and 10% pyroxene.

Eucrite has been defined (Holmes, 1920, p. 94) as "a variety of gabbro formed essentially of bytownite-anorthite and augite", and the term olivine-eucrite is used in this thesis to denote a rock of this type which contains up to 20% olivine, and more than 10% each of clinopyroxene and plagioclase.

It is to be emphasised that the precise limits assigned above to each rock type are solely for convenience and that, in fact, the relationships between these rock types are gradational.

The basic plutonic rocks forming most of the Cuillins are referred to as gabbros throughout this thesis in deference to the precedent established by Harker, although the writer recognises that in a strict sense many of them are eucrites. The only exceptions to this are made in the cases of the Ghrunnda and Ring Eucrites which were specifically named as such by Weedon (1961).

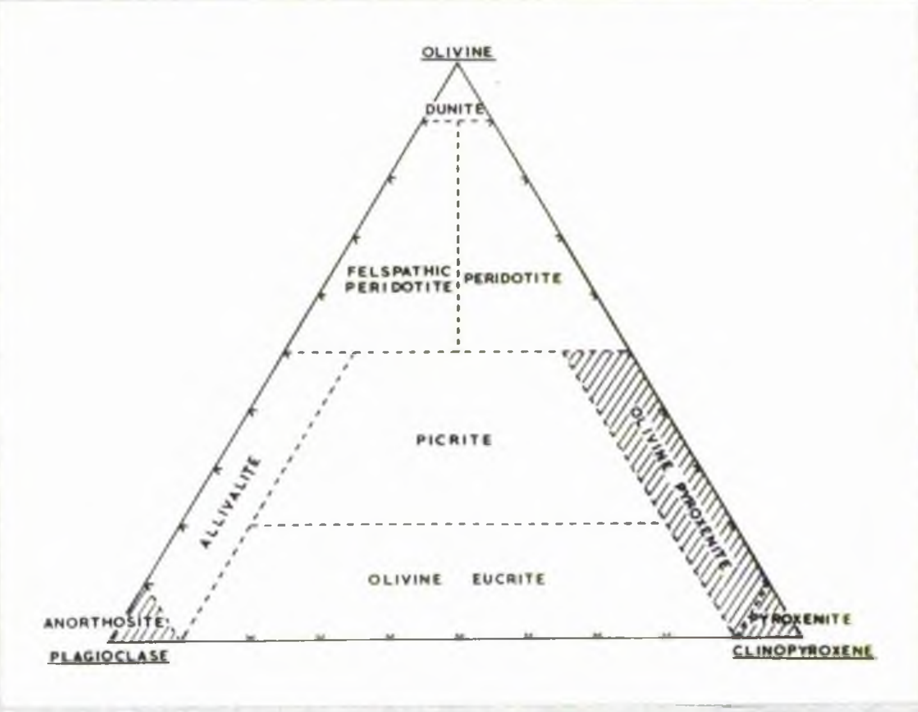

Fig. 2. Relationship between the rock types (Shaded areas are types not featured in this thesis).

III. DYKES INVESTIGATED.

1. INTRODUCTION.

Throughout both of the areas studied the ultrabasic dykes occur as isolated individuals or in small groups. They are catalogued on a numerical basis in order to avoid the confusion which could arise from the use of locality names when several dykes occur within a small area. Most of the dykes are exposed as discontinuous outcrops and individual outcrops are numbered as shown in Map 2 and Fig. 3. The locations of the investigated dykes are given together with some tabulated data in sections 2 and 3 of this chapter.

2. THE STRATHAIRD PENINSULA.

Since the total area exposed is relatively small, all the minor intrusions exposed in this area have been mapped (approximately 570). A map of these intrusions (Map 1) with notes on many of them, and a summary of the principal types are presented as an Appendix to this thesis.

Ten of the mapped intrusions are truly ultrabasic and others have ultrabasic affinities. Five of the ten ultrabasic dykes are described in this thesis. The remaining five ultrabasic dykes are essentially similar to dykes 4 and 5 and, as these are shown in the following chapter to be of the Coire Lagan type, detailed investigation of further examples is unnecessary. Consequently, these dykes are dealt with in the Appendix.

Three of the ten ultrabasic dykes (dykes 1, 2 and 3) were mentioned by Harker (1904, p. 374) but the remaining seven were previously unrecorded as such although some of them may correspond to dykes mapped as "basaltic" by the Geological Survey (Sheet 71).

Dykes 1, 2 and 3 occur in the vicinity of Ben Cleat and the outcrops of these dykes have been carefully mapped on an air photograph (Fig. 3).

The north-west end of dyke 1 is exposed approximately 600 yards south of the mouth of the Scaladal burn. This dyke can be traced from the scree below the cliff face known as Carn Mor, up the cliff, over the brow of Ben Cleat, passing less than 100 yards to the north-east of the summit, and part of the way down the south-east slopes of this hill.

Dyke 2 lies to the south-west of dyke 1. Its most north-westerly outcrop occurs on the face of Carn Mor approximately 135 yards south of dyke 1. It is exposed to the south-east as a series of isolated outcrops along a shallow depression which passes less than 100 yards to the south-west of the Ben Cleat summit.

Dyke 3 occurs at the north end of the hollow between Ben Cleat and Ben Meabost. It is approximately 500 yards north-east of dyke 1 and parallel to it.

The remaining two ultrabasic dykes studied from this area (4 and 5) are located on the west coast south of the village of Elgol (Fig. 4).

Dyke 4 is a single, very conspicuous outcrop (Fig. 5) approximately 50 yards south of the concrete jetty at Elgol. Dyke 5 is also a single

Fig. 3. The locations of dykes 1,2 and 3.

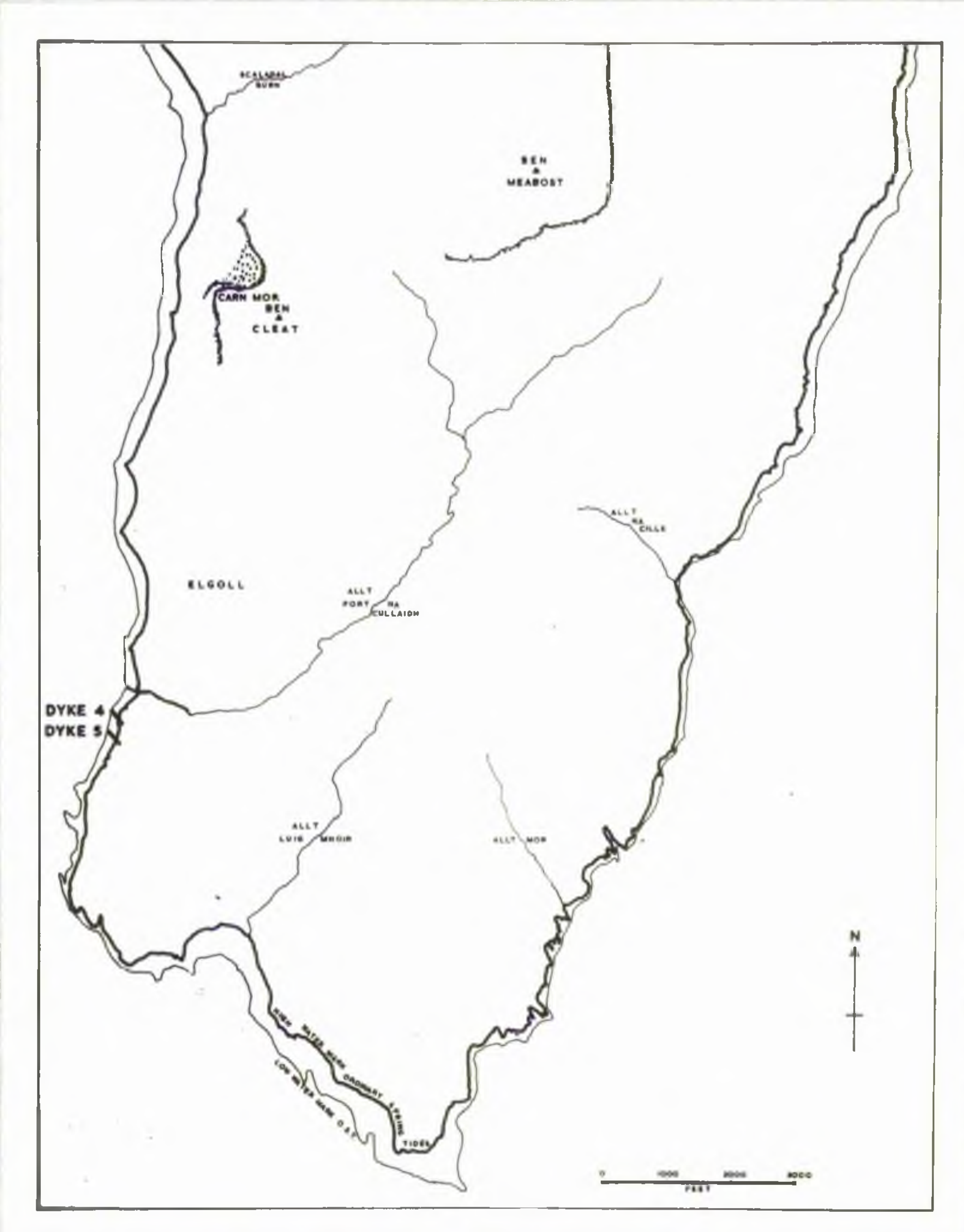

Fig. 4. Map showing the locations of dykes 4 and 5.

Fig. 5. Dyke 4

outcrop on the shore platform but is less prominent than dyke 4. It occurs 110 yards south of dyke 4 and extends from the head of the beach to beyond low water mark. At the lower end of the beach it is covered by boulders. The seaward end of this dyke is shown in Fig. 6.

The number of outcrops, the type of host rock and the dimensions of each dyke are listed in Table 1.

Compared with the dykes on the beach, dykes 1, 2 and 3 are poorly exposed. They consist of three series of isolated outcrops which, with the exception of those on the face of Carn Mor, protrude above the vegetation-covered peat like small, elongated islands of rusty yellowish weathering rock. Contacts between the dykes and the country rock are seldom exposed.

Fig. 6. Dyke 5.

TABLE 1

Data for Dykes 1 - 5.

DYKE	LENGTH (Approx.)	NUMBER OF OUTCROPS	NORMAL WIDTH*	MAXIMUM WIDTH**	HOST ROCK
1	900 yds.	13	30 ft.	35 ft.	Basalt lavas of the Ophimottled Basalt and Basal Lava Groups (Almond, 1964, p. 415).
2	600 yds.	6	?	13 ft.	
3	225 yds.	4	?	17 ft.	
4	40 yds.	1	11 ft.	14 ft.	Olivine dolerite sill.
5	50 yds.	1	4 ft.	5 ft.	Limestone of the Inferior Oolite series.

* i.e. the usual width where both contacts are exposed.

** Where the contacts are not exposed (?) the maximum width given is that of the widest outcrop.

3. THE CUILLINS.

Because of the more difficult terrain and the superabundance of minor intrusions (Harker, 1904, p. 364-370, etc.) only ultrabasic dykes have been mapped in the Cuillins. Thirty of these dykes have been studied in detail and are described in this thesis. The remaining five or six have been examined in less detail and, apart from a tentative attempt to classify them in the following chapter, are excluded from the present research. The locations of the mapped dykes are given below, the dykes not studied in detail being catalogued alphabetically instead of numerically.

In addition to the mapped dykes a few ultrabasic minor intrusions in the area have been intentionally omitted from the present research. The locations of these and the reasons for their omission are given at the end of this section.

It is by no means implied that those mentioned below constitute a complete list of the ultrabasic minor intrusions (other than those of the Coire Lagan type) in the area, as it is more than likely that a few have been overlooked in the course of the mapping. However, all the ultrabasic dykes observed by earlier workers are accounted for and many of those mapped have not been recorded previously.

Dyke 6 is the longest ultrabasic dyke in the Cuillins, extending for more than a mile from the north-western slopes of Sgurr Thuilm across Coire a' Ghreadaidh to the north face of Sgurr a' Ghreadaidh (Map 2). In the upper part of Coire a' Ghreadaidh the second and third outcrops from the south-east end of this dyke are divided longitudinally by a narrow ultrabasic dyke (dyke 7). One of these divided outcrops is shown in the frontispiece.

Sub-parallel to, and about 250 yards south-west of dyke 6 on Sgurr Thuilm is dyke 8. Unlike dyke 6, it does not extend across Coire a' Ghreadaidh but terminates on the south face of Sgurr Thuilm.

Dyke 9 transgresses the north spur of An Diallaid, occupying a conspicuous gully in the west face of the spur (Fig. 7). It is not exposed in the small corrie to the east of An Diallaid but remnants of it can be seen high on the east wall of this corrie.

Fig. 7. The north-west end of dyke 9.

Dyke 10 crosses the main Cuillin ridge 50 yards north of the summit of Sgurr na Banachdich. On the west side of the ridge it disappears under scree within 70 yards and no substantial exposure has been observed to the east of the ridge.

Dyke 11 occurs approximately 250 yards west of dyke 10 on the north side of the Sgurr nan Gobhar-Sgurr na Banachdich ridge. It crosses the top of the small corrie east of An Diallaid. This dyke differs from dyke 10 in many of its properties (see later) and is therefore unlikely to be a continuation of that dyke, despite its location (Map 2).

On the south and south-west slopes of Sgurr nan Gobhar are six ultrabasic dykes. These are dykes 12, 13, 14, 15, 16 and 17. The outcrops of each of these dykes have been carefully mapped on an air photograph (Fig. 8).

Dyke 18 outcrops in the upper part of Coire na Banachdich from where it can be followed up the eastern wall of the corrie until it dies out, some 200 yards west of Bealach Coire na Banachdich.

Dyke 19 crosses the Sgurr na Banachdich-Sgurr Dearg ridge approximately 200 yards south of the former peak. At this point the dyke is vertical (Fig. 9) but as it is traced to the west of the ridge it bends to the north and appears to dip less steeply.

Dykes 20 and 21 are exposed for short distances where they cross the main Cuillin ridge respectively 40 and 70 yards south of Bealach Coire na Banachdich.

Between 50 and 150 yards south of the Inaccessible Pinnacle of Sgurr Dearg is a complex of five small ultrabasic intrusions. These are dykes 22, 23, 24 and 25 and an inclined sheet, - sheet 26. A plan of this complex is given in Fig. 10.

Fig. 8. Locations of dykes 12, 13, 14, 15, 16 and 17.

Fig. 9. Dyke 19 crossing the main Cuillin ridge.

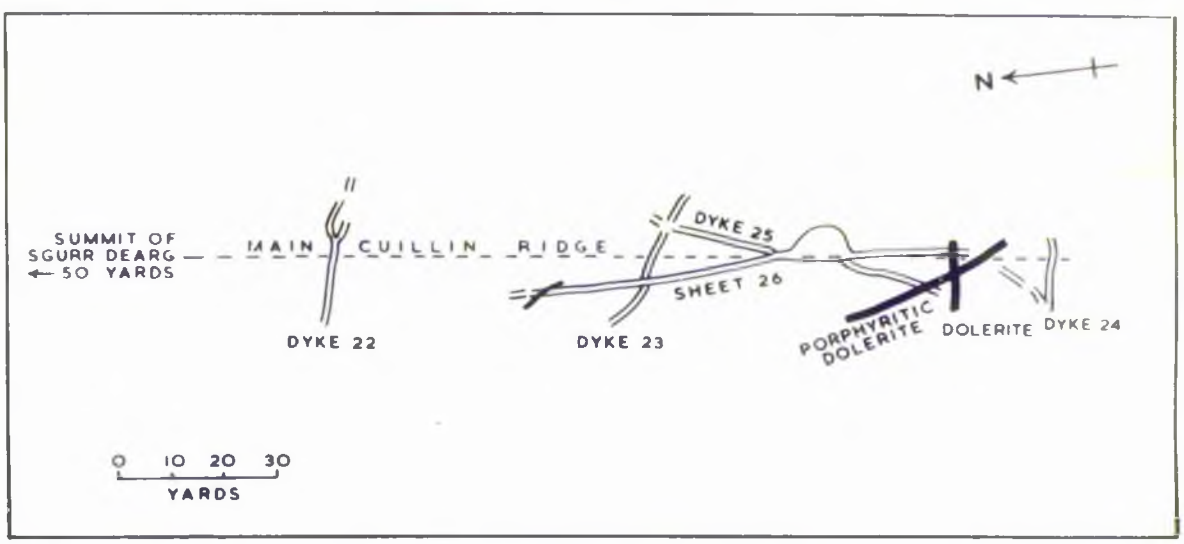

Fig. 10. Plan of the ultrabasic dyke complex south of the summit of Sgurr Dearg.

Outcrops of dyke 27 extend for more than 550 yards from the east end of the Sgurr Dearg spur to the subsidiary ridge known as the Window Buttress (Map 2).

Dyke 28 is exposed in two outcrops more than 500 yards apart. The larger occurs high on the north wall of Coire Lagan almost due north of Lochan Coire Lagan and the smaller on the north side of the Sgurr Dearg spur at its junction with the Window Buttress. It is not absolutely certain that both exposures are part of the same dyke but field and petrographical evidence suggests that they are.

Dyke 29 runs for a short distance down the west end of the Sgurr Dearg spur.

Coir' a' Ghrunnda is a steep sided corrie with its floor rising to the lip of a rock basin in three great steps known as the "Coir' a' Ghrunnda boiler plates". In cross section the floor is slightly convex and consequently, the lowest parts of the floor at any level in the corrie are where it meets the steep sides. This gives rise to two sub-parallel depressions, one down each side of the corrie and these are occupied by ultrabasic dykes: the shorter western one is dyke 30 and the longer eastern one is dyke 31.

Four ultrabasic dykes outcrop in Coire nan Laogh. Dyke 32 is a short, broad dyke near the west end of the lowest transverse rock face in the corrie (Fig. 11). Dyke 33 is a narrow dyke on the north face of the corrie just below the main Cuillin ridge. Like dyke 33, dyke 34 outcrops near the centre of the corrie but is lower down and occupies a prominent gully in the north wall (Fig. 11).

Fig. 11. Gully in the north wall of Coire nan Laogh containing dyke 34. [Dyke 32 is visible in the centre of the photograph.]

Although it appears from the map that dykes 33 and 34 could be parts of the same intrusion they differ in so many respects that they are undoubtedly different dykes. On the east side of the corrie dyke 35 is conspicuous high on the western slopes of Gars-bheinn. The number of outcrops, the type of host rock and the dimensions of the above dykes are given in Table 2.

Dyke A lies to the north-east of dyke 6 and runs sub-parallel to, and just below the ridge of Sgurr Thuilm. It passes approximately 50 yards north of the principal summit of Sgurr Thuilm and extends for a few hundred yards to the north-west of this summit. It has not been followed to the south-east but appears to continue for some distance in that direction.

Two ultrabasic dykes occur in the lower part of Coire na Banachdich. Both occur in single poorly exposed outcrops. Dyke B is exposed 300 yards east of the main fork in Allt na Coire na Banachdich. Dyke C runs parallel to dyke B approximately 30 yards to the north and outcrops 150 yards further up the corrie.

Dyke D is very poorly exposed as a patch of loose blocks where it crosses the main Cuillin ridge 125 yards south of Sgurr na Banachdich. It appears to be a fairly wide ultrabasic dyke with a roughly east-west strike.

On the east shore of Loch Brittle, a few yards north of the mouth of Allt na Buaile Duibhe, are two parallel outcrops of ultrabasic rock. No contacts with the country rock are exposed and they may be two separate dykes or parts of a single one. These are dyke(s) E.

Dyke F is located far to the north of the other ultrabasic dykes on the north side of the deep ravine which drains the corrie Am Bastier to the north-west of Sgurr nan Gillean.

Seven other ultrabasic minor intrusions in the area have been briefly examined but are omitted from the present research. In the corrie Am Bastier a short distance to the west of dyke F is another ultrabasic dyke. It is poorly exposed but is essentially similar to dyke F.

The 6"/mile geological map of the Cuillins prepared by Harker shows an ultrabasic dyke 100 yards east of the summit of Sgurr nan Eag,

TABLE 2.

Data for Dykes 6-35

DYKE	LENGTH (approx.)	NUMBER OF OUTCROPS	NORMAL WIDTH *	MAXIMUM WIDTH **	HOST ROCK
6	1810 yds.	7	10-16 ft.	24 ft.	Mainly gabbro, locally basalt.
7	120 yds.	2	1 ft.	-	Dyke No. 6.
8	1013 yds.	6	10-20 ft.	40 ft.	Gabbro.
9	260 yds.	4(+)	50 ft.	-	Gabbro, locally basalt.
10	80 yds.	1	10-15 ft.	-	Gabbro.
11	100 yds.	1	36 ft.	38 ft.	Gabbro.
12	125 yds.	4	30 ft.	-	Gabbro/basalt. The gabbro of Sgurr nan Gobhar contains large lenses of metabasalt - (Harker, 1904, p. 444).
13	200 yds.	3	10 ft.	15 ft.	
14	680 yds.	6	30 ft.	-	
15	275 yds.	3	30-40 ft.	45 ft.	
16	110 yds.	3	10 ft.	-	
17	45 yds.	2	$2\frac{1}{2}$ ft.	-	
18	475 yds.	3	8"-3 ft.	4 ft.	Gabbro.
19	60 yds.	2	2-3 ft.	-	Gabbro.
20	70 yds.	2	8 ft.	-	Gabbro.
21	40 yds.	1	15 ft.	-	Gabbro.
22	50 yds.	3	3-4 ft.	-	Gabbro.
23	30 yds.	3	2 ft.	-	Gabbro.
24	20 yds.	1	2-3 ft.	-	Gabbro.
25	50 yds.	4	2-3 ft.	-	Gabbro.
26	90 yds.	4	$4\frac{1}{2}$ ft.	-	Gabbro.
27	510 yds.	3	12-35 ft.	-	Gabbro.
28	635 yds.	2	20 ft.	75 ft. ***	Gabbro.
29	80 yds.	2	$2\frac{1}{2}$-6 ft.	-	Gabbro/basalt, similar to Sgurr nan Gobhar.
30	195 yds.	2	$2\frac{1}{2}$-4 ft.	-	Gabbro.
31	560 yds.	3	10-18 ft.	-	Gabbro.
32	50 yds.	1	14 ft.	-	Gabbro.
33	60 yds.	1	1-2 ft.	-	Gabbro.
34	100 yds.	1	5 ft.	-	Gabbro.
35	365 yds.	2	10 ft.	-	Gabbro.

* Some of the dykes show considerable changes in width along their length and in such cases, e.g. Nos. 6, 15, 27 etc., the normal width is given as a range.

** A maximum width is given only where it differs appreciably from the normal width.

*** A maximum width of 75 feet has been recorded for dyke 28 but the dyke is very poorly exposed at this locality and this value may be very inaccurate.

but this could not be located during the present research. However, blocks of ultrabasic rock were found in a deep cleft a short distance east of Harker's locality and these may correspond to the mapped dyke. As the exposure is inadequate for more than an identification of the rock, this dyke is omitted from the present research.

A very short ultrabasic dyke cuts the gabbro a few yards from the margin of the Sgurr Dubh intrusion on the west side of Coir' a' Ghrunnda. This dyke has been omitted because it is poorly exposed and very deeply weathered.

Also omitted is a dyke on the south flank of Sgurr nan Eag recorded by Weedon (1961, fig. 1) the feeder dyke of the Gars-bheinn sills (Weedon, 1960) and a long dyke crossing Coir' a' Chruidh which, according to Harker, is a feeder of the Sgurr Dubh "laccolite". The "laccolite feeder" dyke is mineralogically and petrographically identical to several of the dykes studied in this research.

Drever and Johnston (1958, text-fig. 4) recorded two outcrops of ultrabasic rock on the Coire Lagan side of the west spur of Sgurr Dearg. One of these, at the west end of the spur, is very large. The other is elongated with a northward trend and lies to the south-east of the first. They interpreted these as exposures of a "thick dyke steeply inclined to the south-west". The writer re-examined these outcrops and observed that the south-eastern body of ultrabasic rock dips very steeply to the west. As the outcrop to the north-west is at a higher altitude, the two outcrops cannot be parts of a single intrusion as suggested by

Drever and Johnston. The larger outcrop consists mainly of loose blocks surrounded by scree and there is little evidence of its original form. Due to the uncertain relationships of these outcrops they are not included in the present research.

The ultrabasic dykes of the Cuillins are typically discontinuous, often dying out for no apparent reason only to reappear some distance away along the strike. Individual outcrops are well-exposed except where they are surrounded by scree.

IV. CLASSIFICATION OF THE ULTRABASIC DYKES.

It appears from the work of Harker (1904), Bowen (1928) and Drever and Johnston (1958) that there are at least three suites of ultrabasic dykes in south-west Skye, namely the "early feeder" dykes, the "later" large xenolithic dykes and the "later" small dykes of the Coire Lagan type. However, despite Harker's belief that they belonged to different periods of intrusion, the dykes of the first two suites are petrographically very similar, and Drever and Johnston (1958, p. 464) observed that "for some of those dykes, there is no unambiguous field evidence on which such a distinction can be made". In Weedon's (1960, p. 44) opinion, "the ultrabasic dykes mostly belong to one period, and not two as envisaged by Harker".

Since ultrabasic dykes markedly different from the Coire Lagan type co-exist with those studied by Drever and Johnston (1958) it is beyond doubt that there is more than one type of ultrabasic minor intrusion in south-west Skye. However, little was known from previous work about the exact number of types or the differences between them.

In the present research particular attention has been paid to ultrabasic dykes which differ in any way from those of the Coire Lagan type and an attempt is made below to classify these dykes. Some of them differ only slightly from the typical dykes of the Coire Lagan type, and are therefore classified along with them. Since no significant chemical or mineralogical differences exist between the ultrabasic dykes, less fundamental criteria must be employed in order to classify them.

Drever and Johnston (1958) differentiated between the "smaller" dykes (of the Coire Lagan type), in which cognate xenoliths are rare or absent, and the "larger and often xenolithic" dykes. The presense of ultrabasic xenoliths in the dykes is almost certainly independent of local conditions at the time of intrusion (chapter XVIII) and is, therefore, a relatively satisfactory basis on which to classify the dykes. Such a classification gives the following results :-

(i) Dykes free from cognate xenoliths :-	4, 5, 17, 19, 22, 23, 24, 25, 26 and 32.
(ii) Dykes in which cognate xenoliths are rare:-	10 and 18.
(iii) Dykes containing abundant cognate xenoliths:-	1, 2, 3, 6, 8, 9, 11, 12, 13, 14, 15, 16, 20, 21, 27, 28, 29, 30, 31, 33, 34 and 35.

Dyke 7 contains numerous ultrabasic xenoliths but, before it can be classified, the possibility of those being accidental xenoliths from its host (dyke 6) must be considered. The xenoliths include fragments of dunite and banded felspathic peridotite which cannot be matched with rock from dyke 6. They are, therefore, cognate xenoliths and the dyke can be placed in class (iii).

Dykes 17 and 32 contain abundant accidental xenoliths. The xenoliths in dyke 17 are of fine-grained dolerite and those in 32 are coarse-grained, pinkish weathering, olivine-eucrite similar to much of the Cuillin "gabbro". Some of the dykes contain both accidental and cognate xenoliths (chapter V. 1.e).

The width of a dyke is of little significance as an independent basis for classification but it may sometimes indicate to which class a dyke belongs. Although there is a complete range of widths from less than one foot to more than fifty feet and the widths of individual dykes often vary considerably along their length, there appears to be a tendency for dykes containing cognate xenoliths to be wider than those which do not. Dykes of the former type range from 1 foot wide (dyke 7) to more than 50 feet (dyke 9) with an average width of 17 feet and dykes of the latter type from 2 feet (dyke 23) to 14 feet (dyke 4) with an average width of 5 feet.

The dykes exhibit considerable ranges of textures, grain-sizes and contact relations (chapter V) but, as these properties are dependent mainly on local conditions after emplacement, they cannot be regarded as satisfactory criteria for classification. However, as in the case of width, certain tendencies are apparent which, when combined, substantiate the classification based on cognate xenoliths.

All the dykes of class (i), except dyke 32, have chilled selvedges. They are fine to medium-grained with porphyritic olivine crystals and, again with the exception of dyke 32, which has a microcrystalline groundmass with a granular texture, have groundmass textures in the range variolitic/sub-variolitic/sub-ophitic. These are properties of the Coir Lagan type of dyke (Drever and Johnston, 1958) and it therefore appears that, apart from dyke 32, the dykes of class (i) are of this type.

The dykes containing cognate xenoliths (class iii) may or may not have chilled selvedges but this is often the only difference between otherwise identical dykes, and they cannot be sub-divided on this basis. The "groundmass" (see chapter V.2.d) grain-size varies from very fine, especially in some of the narrower dykes and the margins of wider dykes, to very coarse. The "groundmass" textures are generally interstitial or sub-ophitic. The olivine is porphyritic in the finer-grained rocks but is frequently poikilitically enclosed by the plagioclase and pyroxene crystals in the coarser-grained varieties. Poikilitic texture has not been observed in dykes of the Coire Lagan type.

Although it conforms in many respects with the dykes of class (iii), dyke 7 differs slightly from them in others, most notably in showing a remarkable banding effect (chapter XX.2). It is also the narrowest of these dykes and obviously post-dates one of them.

The two dykes in which xenoliths are rare are more difficult to classify. Dyke 10 has chilled margins and a sub-variolitic texture but is wider than any of the non-xenolithic dykes. The width suggests that it is related to the dykes of class (iii) and, although the other two properties imply an association with the Coire Lagan type of dyke, occasional instances of both have been observed in dykes which contain abundant cognate xenoliths. This dyke also contains a very high percentage of olivine and, since such a high olivine content has not been recorded from dykes of the Coire Lagan type, it is tentatively classed with the dykes which contain abundant cognate xenoliths and frequently contain high percentages of olivine. The classification of this dyke is discussed further in chapter XVI.2.

Dyke 18, on the other hand, has unchilled margins and a medium-grained groundmass with a sub-ophitic texture. It is therefore undoubtedly related to the dykes of class (iii).

It therefore appears that, with the probable exception of dyke 7, the investigated dykes which contain cognate xenoliths are variations of a single type. This is referred to as the Ben Cleat type after the location of dyke 1 which is taken as the type example [It should be emphasized that, although dyke 17 and possibly dyke 10 are of the Ben Cleat type, rare cognate xenoliths can occasionally occur in dykes of the Coire Lagan type (Drever and Johnston, 1958 p. 482)].

The tentative classification outlined above is summarized in Table 3.

The six ultrabasic dykes which have been mapped but not studied in detail all contain cognate xenoliths but in all except dyke A these are small and rare.

Dykes A, D and E are undoubtedly of the Ben Cleat type and dyke B is similar to dyke 10 (although no contacts are exposed).

TABLE 3.

Classification of the ultrabasic dykes studied in this research.

Dykes of the Ben Cleat type.	1, 2, 3, 6, 8, 9, (?)10, 11, 12, 13, 14, 15, 16, 18, 20, 21, 27, 28, 29, 30, 31, 33, 34, 35.
Other (?) types of ultrabasic dyke containing cognate xenoliths.	7.
Dykes of the Coire Lagan type.	4, 5, 17, 19, 22, 23, 24, 25, 26.
Other types of ultrabasic dyke.	32.

Dykes C and F are composed of relatively fresh olivine phenocrysts in a groundmass which is so extensively altered to secondary minerals that no confirmation of their tentative classification as Ben Cleat type is available.

With the exceptions of chapter XX and the Appendix the remainder of this thesis deals only with dykes of the Ben Cleat type, which are hereafter referred to as "the dykes".

V. ULTRABASIC DYKES OF THE BEN CLEAT TYPE.

1. FIELD RELATIONS.

a) General Observations.

As already mentioned, the dykes are usually exposed as series of discontinuous outcrops. Although the ground between the outcrops is often covered by peat or scree, it is evident that even where this covering is absent the dykes are seldom continuously exposed. Two dykes in which discontinuity is particularly noticeable are dykes 6 and 18.

Outcrop 6/2 (Map 2) occurs on a steep, well-exposed gabbro face (Fig. 12) but the dyke terminates abruptly below the top. The upper end of dyke 6 in outcrop 6/7(Fig. 13) is very similar but this appears to be the south-east end of the dyke rather than a discontinuity.

Between outcrops 6/4 and 6/5, which are on opposite sides of Coire a' Ghreadaidh, the gabbro forming the floor of the corrie is well-exposed, but it is not cut by dyke 6. Similarly, a large, perfectly exposed slab of gabbro occurs in the 200 yard long gap between outcrops 18/1 and 18/2 and is not cut by the ultrabasic dyke. The same phenomenon on a smaller scale was recorded from dykes of the Coire Lagan type by Drever and Johnston (1958, p. 471) but there is no accompanying offsetting of the dykes of the Ben Cleat type.

Sometimes the dykes are less resistant to erosion than the country rock and occur in gullies but generally they are more resistant

Fig. 12. Outcrop 6/2 (viewed from the north-west).

and stand above the surrounding rocks like sections of a derelict wall. In outcrops of the former type the edges of the dykes are usually well-exposed, e.g. in outcrop 9/1 (Fig. 7) and outcrops 31/2 (Fig. 14) and 31/3 (which would probably be continuous if the gully was not filled with large boulders). In contrast, the edges of the dykes are rarely well exposed in outcrops of the latter type, some of which, e.g. those on Sgurr Thuilm (particularly 6/1, 6/4 and 8/1), have vertical faces over 20 feet high while others, especially those on Ben Cleat, form low rounded knolls. Where the dykes rise above the

Fig. 13. The south-east end of outcrop 6/7 terminating against gabbro.

Fig. 14. Outcrop 31/2 (viewed from the south).

country rock they are frequently only remnants of the central part of the dyke, e.g. outcrop 1/1, which emerges from the scree below Carn Mor, is less than 7 feet wide although dyke 1 is approximately 30 feet wide.

The weathered surfaces of the dykes range from pale rusty yellow (dykes 1, 9 and 31) to dark reddish brown (dykes 6, 8, 10, 20, 21 and 28). This is probably due to slight differences in the FeO: Fe_2O_3 ratios of the dykes since the darkest weathering dykes (20 and 21) contain exceptionally large amounts of secondary hematite and magnetite. The surfaces of the dykes are usually very rough due to differential weathering of the felspar and ferromagnesian minerals, the former being the more resistant.

Frequently, the width of a dyke cannot be determined in an outcrop because one (or both) of the contacts is not exposed. Occasionally, the width of a dyke cannot be measured in any of the outcrops, e.g., dyke 2, where the maximum width can only be estimated from the width of the gully occupied by the dyke. In addition to the inter-dyke variation in width, there is often considerable variation within an individual dyke. Outcrop 8/1, for example, is only 60 yards long but the dyke varies from 10 feet wide at its north-west end to more than 35 feet near its mid-point, and then back to less than 20 feet at its south-east end. While local changes in width of this type are very common, a more systematic change appears to be present in some of the dykes. As dykes 9, 27 and 29 are traced outwards towards the periphery of the Cuillins, they gradually decrease in width from more than 50 feet to less than 5 feet, 35 feet to less than 12 feet, and 6 feet to 2 feet respectively. However, although it appears to suggest that these dykes originated in the centre of the Cuillins, this variation may be coincidental and of no great significance.

In general, the dykes are vertical or sub-vertical but accurate dips are not readily obtainable because of the nature of the outcrops. Even where a dyke is exposed on a cliff face the dip cannot be determined accurately. The dips of dyke 1 in the outcrops on the cliff face (1/1, 1/2 and 1/3) were measured with a clinometer. The dip of the dyke in the individual outcrops varies slightly, giving an average dip of 86^{o} to the north-east. When the same outcrops were accurately mapped on an air photograph (Fig. 3) and the overall dip of the dyke calculated trigonometrically, the result was 80^{o} to the north-east.

Harker (1904, p. 375) observed that the dykes did not have a constant strike but radiated from a centre in the heart of the Cuillins. This is confirmed by the present investigation and is discussed in a later chapter (XVI). Unlike the width and dip, the strike of an individual dyke is remarkably constant and only dykes 9 (Fig. 7) and 18 show minor local variations. The strikes of the longer dykes were determined from maps prepared by simple surveying and are relatively accurate. The strikes of the shorter dykes, however, were determined with a prismatic compass, which is affected by very strong local magnetic anomalies in the Cuillins (Harker, 1904, p. 113, Drever, 1963), and consequently, may not be particularly accurate. Occasionally, dykes appear to converge, e.g. those on Sgurr nan Gobhar and Ben Cleat. Dykes 1 and 2 differ in strike by 9^{o} and, if the strikes are constant, must converge less than half a mile west of the coast. [In a strict sense this should be regarded as divergence rather than convergence].

Two commonly recurring features of the dykes are the longitudinal and transverse joints. The sub-vertical longitudinal joints are generally a few inches apart and tend to be very persistent. Joints of this type are particularly prominent in dyke 31 (Fig. 15). Despite their persistence they rarely penetrate xenoliths (Fig. 16). They are probably due to weathering along lines of weakness in the dyke caused by contraction on cooling.

Transverse joints are extremely common and divide the dykes into blocks, usually with a rhombic cross-section. They are most prominent on the sides of the wall-like outcrops, e.g. 1/1 and those of dyke 35, but are also visible on non-vertical faces (Fig. 17). The cause of these joints is discussed below (chapters V.1.f and XIV.2.c).

A feature peculiar to dyke 9, particularly in outcrops 9/3 and 9/4, is the presence of deep pod-shaped pits often more than 6 inches

Fig. 15. Longitudinal joints in outcrop 31/3.

Fig. 16. Longitudinal joints terminating against cognate xenoliths in outcrop 31/2.

Fig. 17. Transverse joints in outcrop 3/4.

long (Fig. 98). These pits are sometimes several inches deep and do not appear to be caused by the weathering out of large xenoliths which are relatively rare at these localities.

b) Contact Relations.

The rocks intruded by the dykes range from fine-grained basalts to coarse-grained gabbros and eucrites. The wall rock often varies along the length of a dyke and two of the dykes locally intrude fine-grained basic rocks which may be gently inclined sheets.

The contacts between the dykes and the country rocks are particularly susceptible to erosion and, consequently, are seldom well-exposed. However, in several of the outcrops one of the contacts is visible and occasionally both are exposed. The unexposed north-east contact in outcrop 1/10 was sampled by diamond drilling with a Dinky drill (Drever, 1964).

A few of the dykes have chilled selvedges but most are in unchilled contact with the country rock. Where a dyke is not chilled against the country rock it may or may not become much finer-grained towards the margins. The nature of the contact sometimes varies along the length of a dyke and extreme cases exist where a dyke which is not chilled against the country rock at one point has a tachylitic selvedge at another. Three such cases have been observed: these occur in outcrops 10/1, 18/3 and 29/1. In the case of dyke 10 the margins of the dyke show both types of contact but in the other two the dyke is unchilled against the country rock and has offshoots with chilled margins (chapter XIII).

Where a dyke is in unchilled contact with different wall rocks any decrease in grain-size is more pronounced towards contacts with fine-grained rocks than those with coarse-grained types. The outcrops with exposed contacts, their wall rocks and various marginal relations are summarized in Table 4. Many of these contacts are described in more detail below (chapter V.2.j).

Where the dykes have chilled contacts it is evident that the country rock was at a considerably lower temperature than the dyke material at the time of intrusion. Where the dykes are not chilled, however, the following possibilities exist :-

...s of the dykes
...tacts.

MARGINAL RELATIONSHIP
Unchilled. The dyke becomes very fine-grained at the contacts.
Unchilled. The dyke becomes very fine-grained at the contact.
Unchilled. The dyke becomes fine-grained at the contact.
Unchilled. The dyke becomes finer-grained at the contacts.
Unchilled. The dyke does not become finer-grained at the contact.
Unchilled. As the N.E. contact except against the fine-grained rock where the dyke becomes finer-grained at the contact.
Unchilled. The dyke becomes fine-grained at the contact.
Unchilled. The dyke does not become finer-grained at the contact.
Unchilled. The dyke becomes very fine-grained at the contact.
Chilled selvedge.
Chilled selvedge.
Chilled selvedge.
Unchilled. The dyke becomes fine-grained at the contact.
Chilled selvedges.
Unchilled. The dyke becomes fine-grained at the contact.
Unchilled. The dyke becomes very fine-grained at the contact.
Unchilled. The dyke becomes fine-grained at the contact.
Unchilled. The dyke becomes fine-grained at the contact.
Unchilled.
Unchilled. The dyke becomes very fine-grained at the contact.
Unchilled. The dyke becomes very fine-grained at the contacts.
Unchilled. The dyke becomes fine-grained at the contact.
Unchilled. The dyke becomes slightly finer-grained at the contacts.
As 31/2.
Unchilled. The dyke is very fine-grained immediately adjacent to the contacts.

TA

Marginal relat
with exposed

DYKE	OUTCROP	CONTACT	WALL ROCK
1	1/2	Both	Basalt
	1/10	N.E.	Basalt
6	6/6	N.E.	Gabbro (coarse-grained)
	6/7	Both	Gabbro (coarse-grained)
9	9/1	N.E.	Gabbro (coarse-grained)
		S.W.	Gabbro: locally a fine-grained basic rock.
	9/2	S.W.	Gabbro (coarse-grained)
	9/3	N.E.	Gabbro (coarse-grained)
	9/4	N.E.	Fine-grained basic rock.
10	10/1	S.	Gabbro (medium-grained)
		N. (East end)	Gabbro (medium-grained)
		N. (centre)	Gabbro (medium-grained)
		N. (West end)	Gabbro (medium-grained)
11	11/1	Both	Gabbro (coarse-grained)
15	15/1	N.E.	Gabbro (coarse-grained)
16	16/2	S.W.	Metabasalt
18	18/3	Both	Gabbro (coarse-grained)
27	27/1	N.	Gabbro (coarse-grained)
	27/2	N.	Gabbro (coarse-grained)
	27/3	S.	Gabbro: locally metabasalt.
29	29/1	Both	Basalt
30	30/1	W.	Gabbro (coarse-grained)
31	31/2	Both	Gabbro and eucrite
	31/3	Both	Eucrite
33	33/1	Both	Gabbro

(i) the dyke was emplaced at such a low temperature that it did not chill against cold country rock,

(ii) the country rock was sufficiently hot at the time of intrusion to prevent chilling and

(iii) the contacts were initially chilled but were subsequently removed.

The first of these possibilities can be disregarded as the presence of chilled margins on some of the dykes indicates that ultrabasic dykes of this type were not emplaced at very low temperatures. In addition, at the moderate pressures under which the dykes must have been emplaced (chapter XV) such rocks would be mobile only at relatively high temperatures.

If the country rock was hot when the unchilled dykes were intruded then, either the chilled dykes were emplaced towards the end of a prolonged period of dyke intrusion when significant cooling of the country rock had occurred or the country rock was hotter in some areas than in others. Neither of these alternatives, however, can account for the two extreme contact relationships occurring within a single outcrop such as 10/1.

A chilled contact might be mechanically removed by continued flow of the dyke magma and prolonged contact with the hot magma could heat the wall rock sufficiently to prevent further chilling. In such a case initially chilled offshoots could not be removed, thus producing contact relations of the type occurring in dykes 18 and 29. However, no other evidence of the operation of such a process has been observed in the dykes. Xenoliths of country rock, which would appear to be an inevitable by-product of this process are seldom abundant and fragments of chilled margin have not been observed in the dykes. In addition, since the flow velocities are very small near the walls of a dyke (chapter XI.3) the frictional forces acting on the walls during flow are slight.

It appears, therefore, that the lack of chilled selvedges on the majority of the dykes is probably due to a combination of the second and third possibilities.

The grain-size variations in the margins of a dyke where it is in juxtaposition with different wall rocks could be attributed to the finer-grained wall rocks having higher thermal conductivities than the coarser-grained varieties.

Near the mid-point of outcrop 10/1, the chilled marginal material of the dyke has locally penetrated the wall rock at both contacts to depths of over two feet, forming the breccias observed by Bowen (1928, p. 154). These are described below (chapter V.2.j).

c) Relations with Other Minor Intrusions.

According to Harker (1904, p. 375) "the ultrabasic dykes of the Cuillins cut all other rocks which they encounter, including the inclined basic sheets, and are therefore the youngest rocks in the.........district" and "the ....dykes, in Strathaird, belong to the same ....group, though direct evidence tells us only that they cut the basic sills of the great group, and are not themselves cut by any other dykes".

The observed relations are not in keeping with Harker's statements. Although the ultrabasic dykes do cut many minor intrusions they are frequently cut by others. A summary of these relations is presented below.

Dyke 1 is cut longitudinally by two basic dykes. The first, cutting outcrop 1/2, is a seven foot wide dyke of olivine dolerite (Fig. 18) which is almost completely decomposed to brown earth apart from three zones six inches thick at the chilled margins and in the centre. The second, cutting outcrop 1/5, is only nine inches thick and is almost certainly a different dyke from that cutting outcrop 1/2 since it is absent from the intervening outcrops.

Fig. 18. Partly decomposed basic dyke cutting outcrop 1/2.

Basic rock is exposed in the 150 yard long gap between outcrops 1/5 and 1/6. [This rock is formed of a sub-ophitic intergrowth of clinopyroxene and basic plagioclase with abundant interstitial glass. Olivine and magnetite are present in minor amounts, the former generally pseudomorphed by antigorite, and the rock contains large vesicles filled with prehnite showing well developed "bow-tie" structure (Kerr, 1959, p. 418.] The gap may be due to a discontinuity of dyke 1, but the basic rock bears little resemblance to the basalt country rock and, although no contacts between this rock and the dyke are exposed, it appears probable that it is an intrusion which cuts the ultrabasic dyke. From the location of the exposure (Fig. 3) it appears to be part of a sill mapped by the Geological Survey (sheet 71), and regarded by them as one of the "great group of basic sills". However, it differs petrographically from these sills as described by Harker, the difference probably being due to the fact that many of Harker's sills are actually lava flows (Kennedy, 1931, p. 178).

Dyke 2 is cut longitudinally by at least one basic dyke which is chilled against the ultrabasic rock.

Dyke 6 is cut transversely by several narrow basic dykes in addition to dyke 7 which cuts outcrops 6/5 and 6/6 longitudinally. One of these is itself cut by a later basic dyke parallel to dyke 6. In outcrop 6/5 the dyke is cut by a sub-horizontal basic sheet which also cuts dyke 7 and is chilled against both ultrabasic dykes. In outcrop 6/6 both ultrabasic dykes are cut by a few thin doleritic veins (Fig. 19) and two narrow dykes, one of which (Fig. 20) is lime-rich (Drever and Johnston, 1966).

Fig. 19. Doleritic vein cutting dykes 6 and 7.

At the lower end of outcrop 6/7 is a small complex of basic dykes (Fig. 21) some of which cut dyke 6. Higher up the same outcrop dyke 6 is cut by several other narrow basic dykes, one of which contains a large xenolith of the ultrabasic dyke (Fig. 22).

Dyke 8 is cut by four basic dykes and a sub-horizontal basic sheet, all of which are chilled against the ultrabasic dyke.

Fig. 20. Lime-rich dyke (foreground) cutting dykes 6 and 7.

Fig. 21. Complex of basic dykes at the lower end of outcrop 6/7.

Fig. 22. Xenolith of dyke 6 in a basic dyke cutting outcrop 6/7.

Dyke 9 cuts two narrow dykes near its north-west end and is itself cut by a 1 foot thick inclined basic sheet (Fig. 23).

Dyke 10 is cut by a single narrow basic dyke.

Dyke 11 is cut longitudinally by a six inch thick dolerite dyke, from which stringers extend into the ultrabasic dyke, and transversely by an 18 inch thick basic sheet which dips gently to the east.

Dykes 12, 14 and 15 are all transgressed by small basic dykes and a 15 inch wide dyke runs along the centre of the dyke in outcrop 15/1 (Fig. 24).

Dyke 18 is cut by four narrow basic dykes all of which are chilled against the ultrabasic dyke.

Fig. 23. Inclined basic sheet cutting outcrop 9/1.

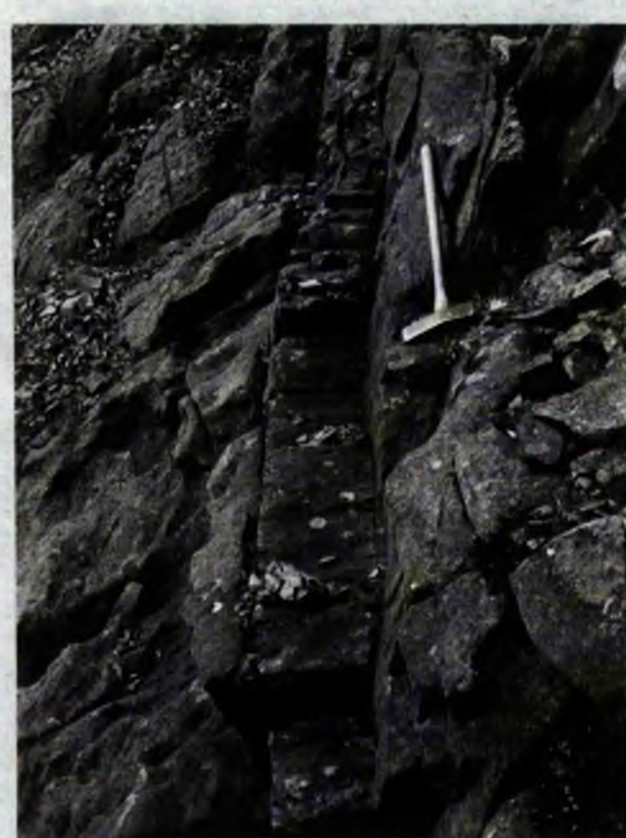

Fig. 24. Basic dyke cutting dyke 15 longitudinally.

Dykes 20 and 21 are each cut by two narrow basic dykes.

Dyke 27 is cut longitudinally for approximately 10 feet by a basic dyke which pinches out at both ends. Dyke 27 also cuts at least two basic dykes.

Dykes 28 and 29 cut several small basic dykes and are each cut by at least one minor intrusion.

Dykes 30 and 31 cut many narrow basic dykes in the lower part of Coir' a' Ghrunnda, e.g. Fig. 25, but these basic dykes, which cut the Outer Gabbro (Weedon, 1961), appear to be absent higher up the corrie where dyke 31 cuts the Ghrunnda Eucrite (Weedon, 1961). A single small basic dyke cuts dyke 30 (Robertson, 1963, p. 19).

Fig. 25. Dyke 31 cutting a narrow basic dyke.

The remaining dykes of the Ben Cleat type (3, 13, 16, 33, 34 and 35) have not been observed to intersect any other minor intrusions.

It appears, therefore, that the ultrabasic dykes are earlier than the inclined basic sheets and the majority of the basic dykes. However, there is at least one group of basic dykes which is earlier than the ultrabasic dykes and these dykes generally strike at approximately right angles to the ultrabasic dykes. These relationships and the evidence they present of the relative age of the ultrabasic dykes are discussed in chapter XVI.

d) Banding etc.

Various planar structures occur in the dykes and the principal types are summarized in Table 5. These structures are studied in more detail in chapter XII.

TABLE 5

Types of planar structure occurring in the dykes

TYPE	APPEARANCE IN THE FIELD	OUTCROPS IN WHICH IT OCCURS
Marginal Lamination	Closely spaced fractures parallel to the margins which impart a fissility to the edges of the dyke.	3/4, 6/4, 9/1, 20/1, 28/2, 30/2.
Sub-horizontal Banding	Rippled effect on vertical and near vertical weathered surfaces.	9/1, 9/3, 9/4, 12/2, 14/5.
Sub-vertical Banding	Rippled effect sub-parallel to the dyke margins on weathered surfaces.	8/1.
Gradational Banding	Small pits on the weathered surface giving a graded bedding effect.	1/2.
Layering	Vertical changes in grain-size on a relatively large scale.	12/2, 14/5.

e) Xenoliths.

The dykes contain cognate* xenoliths which, in the field, appear to be of two principal types: i) - more felspathic and apparently coarser-grained than the dyke rock, ii) - less felspathic and apparently finer-grained than the dyke rock. The majority of the xenoliths appear to be of the first type. Examination of the xenoliths in thin section, however, indicates that a continuous range of types is present (chapter XII. 1).

A relatively common variety of xenolith is composed of alternating bands of rock with different felspar contents (Fig. 26).

Fig. 26. Banded xenolith in outcrop 1/9.

*The cognate nature of the xenoliths can only be determined by microscopic examination but the term is used here for convenience.

A much rarer type of xenolith is one in which a single, very large, arborescent plagioclase crystal encloses abundant smaller olivine crystals (Figs. 27 and 28). These xenoliths are almost invariably broken fragments of larger arborescent plagioclase crystals: those illustrated are the two most complete examples which have been observed. These crystals may be analogous to the "harrisitic" olivine crystals described by Wadsworth (1961, p. 37-39).

Fig. 27. Felspathic peridotite xenolith in outcrop 8/1.

Fig. 28. Felspathic peridotite xenolith in outcrop 1/11.

Although there appears to be a tendency towards slight local concentrations of similar xenoliths, all of the common types are present in each dyke.

Xenoliths more felspathic than the dyke in which they occur are less susceptible to erosion than the dyke rock and usually project slightly above the weathered surface of the dyke (Fig. 29). Extreme differential weathering of these xenoliths produces protruberances (Fig. 30).

Fig. 29. Felspathic peridotite xenoliths in outcrop 3/4.

Fig. 30. Extreme differential weathering of xenoliths in outcrop 1/10.

Xenoliths of this type weather to a paler yellow colour than the dyke (Fig. 31).

Fig. 31. Felspathic peridotite xenoliths in outcrop 29/1.

Xenoliths less felspathic than their host rock are less resistant to erosion and produce depressions in the surface of the dyke on differential weathering (Fig. 32). Such xenoliths usually weather to a darker colour than the dyke. Where xenoliths of this type are very abundant differential weathering causes the interstitial dyke rock to form ridges round the xenoliths (Fig. 33).

Fig. 32. Felspathic peridotite, peridotite and dunite xenoliths in outcrop 3/4.

Fig. 33. Ridges around xenoliths in outcrop 3/4.

The shapes and sizes of the xenoliths are very variable. They range from less than half an inch to more than two feet in length, and may be sub-equant or elongate (Fig. 34), angular (Fig. 35) or rounded.

Fig. 34. Elongated xenolith in outcrop 1/2.

The xenolith content varies locally within a dyke as well as from one dyke to another. In some places cognate xenoliths are rare, while in others they constitute more than 50% of the dyke (Fig. 36).

In some of the dykes cognate xenoliths have been observed within a few inches of the country rock but they appear to be absent at the contacts. The dykes appear to be in sharp contact with the xenoliths and macroscopic indications of assimilation are completely

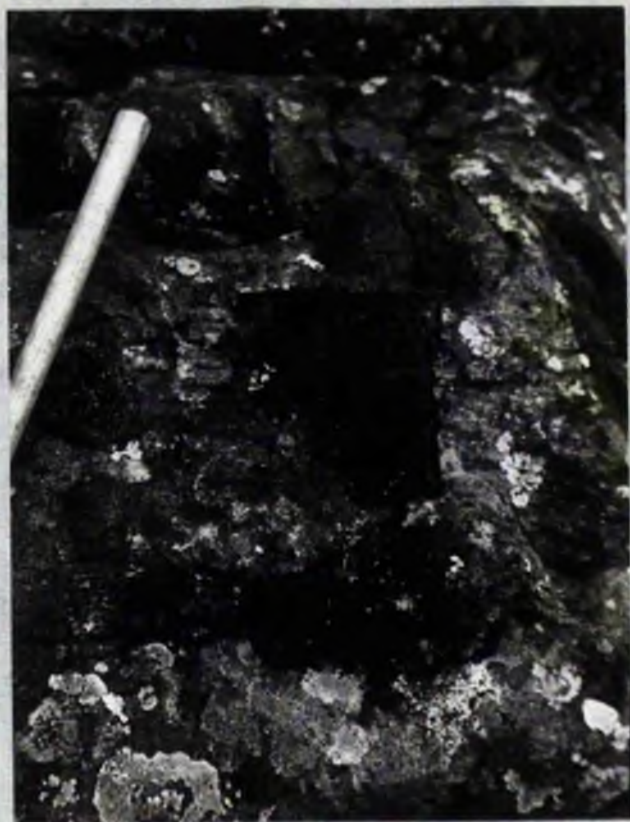

Fig. 35. Angular xenoliths in outcrop 8/1.

Fig. 36. Highly xenolithic vertical face in outcrop 8/1.

lacking (see chapter XII. 3), although occasionally a veinlet of dyke material penetrates a xenolith.

The results of a more detailed study of the cognate xenoliths are presented in chapter XII.

In addition to the cognate xenoliths, the dykes have been observed to contain accidental xenoliths in outcrops 1/2, 13/2 and 27/3. In the first two instances they are rare but in outcrop 27/2 they are very numerous near the north contact at one locality.

f) Offshoots and Veins.

Offshoots and three types of post-intrusive veins (other than the thin doleritic veins belonging to a much later period of intrusion mentioned above) are associated with the dykes.

TABLE 6.

Distributions of offshoots and post-intrusive veins associated with the dykes.

TYPE		APPEARANCE IN THE FIELD	OUTCROP IN WHICH THEY OCCUR
Offshoots			10/1, 18/2, 18/3, 29/1, 31/3
Post-Intrusive	(Pegmatitic (veins	Short, coarse-grained veins	12/3, 14/5.
	(Leucocratic (veins	Alteration veins about ½ inch thick	1/3, 9/1.
	(Thin "red" (veins	Red weathering veins less than ⅛ inch thick. They are veins along which the dyke is highly altered and these are associated with the transverse joints (chapter V.1.a).	Most outcrops.

These are described in more detail in chapter XIV. The offshoots cut only the country rocks but the veins may cut both the country rocks and the dykes although they are generally confined to the dykes. The distributions of the offshoots and different types of post-intrusive veins are listed in Table 6.

Thin quartz veins occur between the north-east edge of the dyke and the gabbro in outcrop 9/1, but the possibility of these being connected with the ultrabasic dyke appears remote.

2. MINERALOGY AND PETROGRAPHY.

a) Composition of the Dykes.

The dyke rocks are composed primarily of forsteritic olivine, calcic plagioclase and clinopyroxene with accessory chrome spinel and magnetite. Occasionally, small patches of brown glass occur and these often contain crystals of a second kind of clinopyroxene.

The primary minerals are never completely unaltered but in most of the dykes secondary minerals are not extensively developed. The common secondary minerals are serpentine, bowlingite, chlorite and magnetite. Epidote, hornblende, biotite, sericite and carbonate are less common.

The relative proportions of the primary minerals vary from dyke to dyke and within individual dykes. As these variations are described and discussed at length in later chapters it need only be mentioned here that the margins of a dyke are often poorer in olivine and richer in plagioclase and pyroxene than the centre. Occasionally, the relative amounts of the primary minerals vary slightly along the length of a dyke (chapter V. 2.i).

The grain-sizes and textural relationships of the constituent minerals also vary, often considerably, from dyke to dyke and within many of the dykes.

b) Olivine.

The olivine, which is pale to dark green in the hand specimen, is generally colourless in thin section. The only notable exceptions to this are in dykes 33, 34 and 35 where the crystals are slightly coloured (see below).

Perfectly developed crystal faces are common but relatively few crystals are bounded on all sides by such faces and the majority of the crystals are subhedral. The olivines range from sub-equant to elongate with a length:breadth ratio greater than 8:1, but for most of the elongate crystals this ratio is less than 3:1.

The skeletal crystals common in ultrabasic minor intrusions (Drever and Johnston, 1957) are extremely rare in the dykes. Only two good examples of such crystals have been observed in the course of the present research, both occurring in dyke 2 (Figs. 37 and 38). Neither of these are extreme skeletal forms such as those illustrated by Drever and Johnston (1957, text figs. 5-10) and one (Fig. 37) may

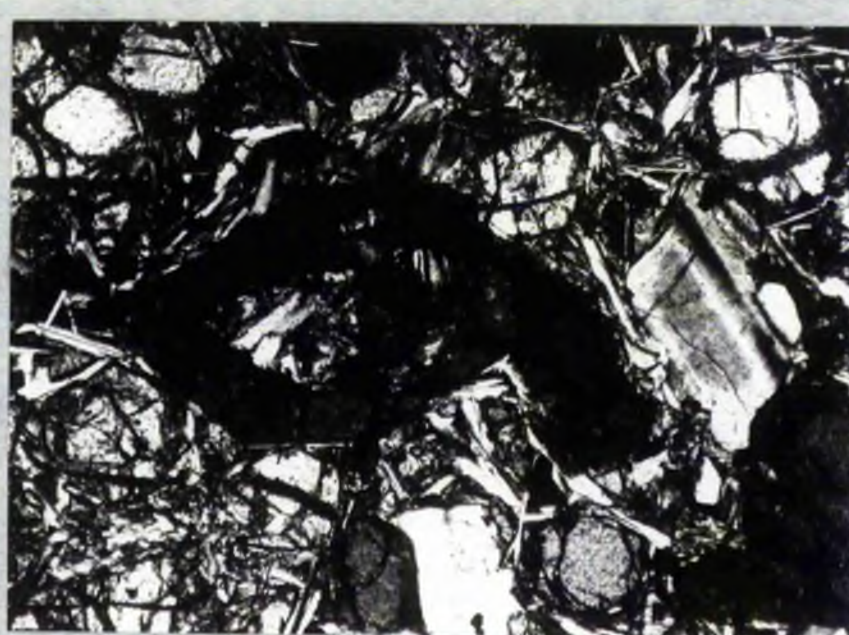

Fig. 37. Skeletal olivine crystal from dyke 2.
X 50; crossed nicols.

be a section cut parallel to an embayed crystal face. The other (Fig. 38) closely resembles some of the large harristic olivines described by Wadsworth (1961, p. 38-39 and figs. 14 and 15) from the layered ultrabasic rocks of Rhum.

Fig. 38. Skeletal olivine crystal from dyke 2. X 15; crossed nicols.

In the majority of the dykes the length of the olivine crystals in a single specimen ranges from less than 0.1 mm. to more than a centimetre, but very large examples are generally rare. The average size of the crystals varies from dyke to dyke and usually within individual dykes. Changes in the average size within a dyke are generally caused by a variation in the proportion of small crystals relative to large ones, although occasionally there is also a slight variation in the maximum size which is not entirely attributable to the sampling error. Because the average size can, and frequently does, vary without a corresponding change in the maximum size, the range in which most of the crystals fall, although only estimated visually, is a better criterion for comparative petrography than the maximum size (Table 7 etc.).

While olivine is always the dominant mineral in the central parts of the dykes, where it sometimes exceeds 70%, it may be almost completely absent from the margins.

No evidence of zoning can be detected in crystals cut approximately normal to an optic axis (Tomkieff, 1939) and it may be assumed that the olivine crystals are of uniform composition.

One of the most significant features of the olivine is the number of crystals which display translation lamellae (Chudoba and Frechen, 1950). The lamellae are generally best developed in some of the larger crystals where more than thirty separate translation planes may be present (Fig. 39). The lamellae are of varying widths and the

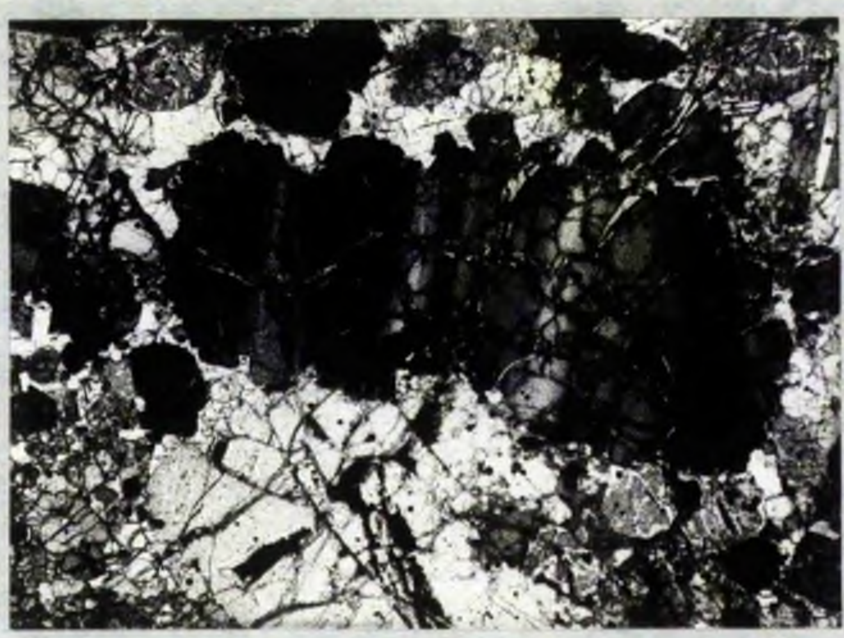

Fig. 39. Olivine crystal from dyke 1 showing multiple translation lamellae. X 15; crossed nicols.

extinction positions of adjacent lamellae may differ by as much as 12^{o}. The proportion of the olivine crystals which exhibit this phenomenon differs not only from one dyke to another but between two thin sections cut from the same specimen. The proportion of lamellate olivines in a specimen is unrelated to its position in the dyke and such crystals appear to be randomly distributed throughout the individual dykes. Translation lamellae may be developed in more than 20% of the olivine crystals in a thin section but the averages for the dykes are generally less than 5%. Olivines showing translation lamellae are present in all the dykes but are commonest in dykes 1, 3, 6, 8, 9, 18 and 33.

The olivine in dykes 33 and 34 is pale brownish grey due to slight clouding. Some of the crystals are more clouded than others and the clouding frequently tends to be more intense in narrow bands (Fig. 40) within a crystal. The bands are parallel to,

Fig. 40. Clouded olivine in dyke 33. X50; plane polarised light.

and apparently coincide with individual translation lamellae. This may only be a reflection of the parallelism of both the bands and the lamellae to the (100) cleavage, but the fact that the most intensely clouded crystals always show well-developed translation lamellae suggests that there is a genetic connection between the two phenomena. Similar, but less intense clouding of the olivine crystals occurs in dyke 35. Usually the olivine is only slightly altered but occasionally it is completely pseudomorphed by serpentine etc. (chapter V.2.g).

c) Chrome Spinel.

An opaque to translucent red-brown mineral forms between 1 and 2% of the dyke rocks. It occurs as small crystals (less than 1 mm. across) with well-developed, square cross-sections. These crystals are evenly disseminated throughout the dykes as inclusions in all three of the principal minerals.

Harker (1904, p. 69-71) described similar small opaque and translucent brown crystals in the ultrabasic intrusion of Sgurr Dubh as chrome magnetite and picotite respectively. Brown (1956, p. 25) concluded that the opaque mineral in the Rhum ultrabasic rocks was chrome magnetite and Drever and Johnston (1958, p. 483) referred to the small opaque and translucent crystals in picritic dykes as chrome spinels. It appears probable that the opaque minerals in all of these rocks and in the xenolithic dykes are basically similar and the term employed by Drever and Johnston is adopted here. No attempt is made to discriminate between the various opaque, semi-opaque and translucent forms.

d) Plagioclase.

Unlike those of the olivines, the ranges of shapes and sizes of the plagioclase crystals in a single specimen are relatively small but they vary considerably from one dyke to another and often locally within individual dykes. The total range occurring in the dykes is from sub-equant crystals more than half a centimetre long (Fig. 41) through stubby laths (Fig. 42) and elongate laths (Fig. 42) to minute acicular crystals identifiable only under very high magnification. Where a dyke is chilled against the country rock the plagioclase grades from tiny acicular crystals near the contact to elongate laths in the centre of the dyke. The plagioclase in the centres of dykes with unchilled contacts varies from large sub-equant crystals to elongate laths and may or may not decrease in size (with a corresponding change in habit) towards the contact.

Occasionally, a few medium-sized, sub-equant forms co-exist with laths, usually in the marginal parts of a dyke. The sub-equant crystals may be phenocrysts which are not discernable in the centres of the dykes due to an increase in the size of the "groundmass" felspars. [The term "groundmass" is used only to indicate the pyroxene and plagioclase and does not imply that it is considerably finer-grained than the olivine, although this is often the case]. This possibility is considered further in chapter VIII. A summary of the shapes and sizes of the plagioclase crystals in the centres and margins of the dykes is presented in Table 7.

Plagioclase forms between one-fifth and one-third (by volume) of the dykes. The crystals all consist of an unzoned calcic core with normally zoned margins. Large sub-equant crystals have a very large core and narrow marginal zones. In some of the dykes, e.g. 31, the marginal zoning is slight. In the smaller, elongate laths the unzoned cores make up much less of the crystals. A few of the laths appear to be continuously zoned throughout, but these may be cut with the plane of the section passing only through the outer, zoned part of the crystal.

The plagioclase, like the olivine, exhibits varying degrees of alteration (chapter V.2.g).

e) Pyroxene.

The pale brown clinopyroxene is usually the least abundant of the three principal minerals in the dykes. Crystal faces are never developed and the shapes of the crystals are governed by those of the neighbouring olivine and plagioclase crystals.

The size and shape of the clinopyroxene crystals vary sympathetically with those of the plagioclase. Where the felspars are large and sub-equant the pyroxene occurs as similar crystals (Fig. 41),

Fig. 41. Large, sub-equant plagioclase and pyroxene crystals in the centre of dyke 1. X50; crossed nicols.

but where the plagioclase is present as laths and elongate laths the pyroxene crystals are smaller, usually elongated and often wedge-shaped (Fig. 42).

Fig. 42. Plagioclase laths and small, often tapering, pyroxene crystals near the margin of dyke 29. X 15; plane polarised light.

Throughout the entire group of dykes clinopyroxene crystals range from sub-equant crystals more than 3 mm long to tiny grains barely recognisable under a very high magnification. However, the range of crystal sizes in any one specimen is relatively small and the maximum length is a more useful criterion for comparative petrography than that of the olivine crystals (Table 7).

Many of the crystals show the slight disorientation of parts of the crystal generally regarded as being the result of strain during or after crystallization.

Of the three principal minerals the pyroxene is usually the least altered to secondary minerals (chapter V.2.g).

f) Glass.

In a few of the dykes small, sub-spherical, patches of brown glass are present, but they are only common in dykes 10 and 27. The patches in dyke 27 are strongly coloured but those in dyke 10 are only faintly brown.

They are usually between 1 and 2 mm in diameter and contain elongated, often acicular, crystals of a colourless clinopyroxene ($2V_\gamma$ = approx. $57\frac{1}{2}^{\circ}$), small chrome spinels and occasionally a little carbonate. The glass is occasionally isotropic but in most of the patches it is partially devitrified to a microcrystalline aggregate with very low birefringence. The amount of pyroxene varies from patch to patch and the two observed extremes are shown in Figs. 43 and 44. The elongate clinopyroxene crystals, which may be as long as 1 mm, might have been present prior to the chilling of the glass but their shape, mode of occurrence and difference from the "groundmass" pyroxene in the dyke suggest that they are devitrification products.

In view of the relatively coarsely crystalline nature of the dyke rocks, the presence of glass appears to be anomalous. Direct evidence indicates only that these patches formed after the crystallization of the chrome spinel, although the fact that they are interstitial to the olivine crystals implies that they were formed after the crystallization of the olivine.

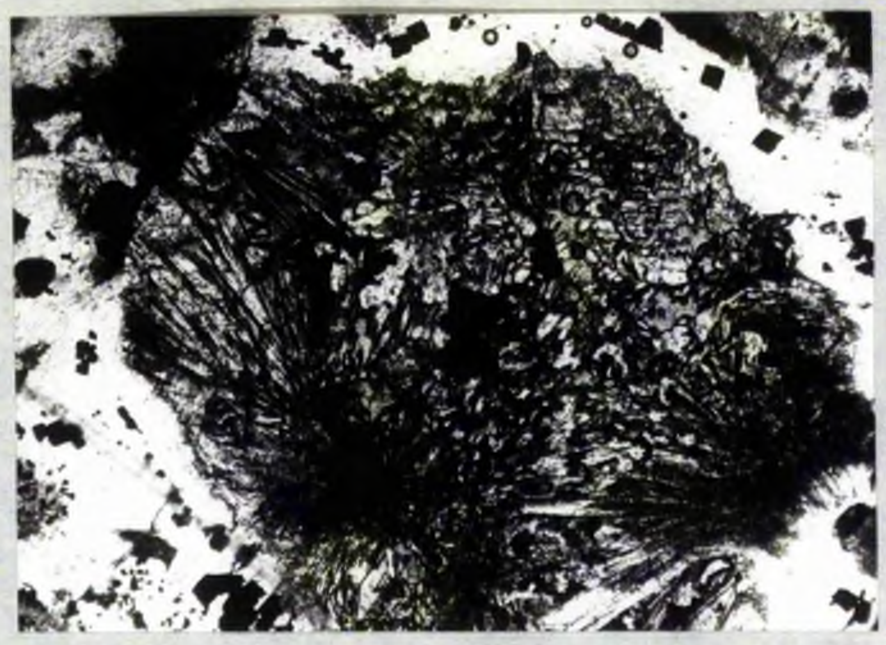

Fig. 43. Glassy patch containing abundant clino-pyroxene crystals in dyke 27. X 50; plane polarised light.

Fig. 44. Glassy patch containing relatively few pyroxene crystals in dyke 27. X 50; plane polarised light.

g) Secondary Minerals.

A colourless - pale yellow serpentinous mineral, identified as antigorite, replaces olivine in all the dykes. It is generally confined to the typical curving cracks in the olivine crystals but in some of the dykes it is more extensively developed and in a few the olivines are completely pseudomorphed by it.

Where plagioclase is in contact with olivine or pyroxene a colourless - pale green pleochroic chlorite is frequently developed. In most of the dykes it forms very narrow zones at the crystal interfaces but in some of the more altered rocks chlorite has completely replaced many of the plagioclase crystals.

A second, slightly different chlorite also occurs in a few of the dykes. It is only very faintly green, has a higher birefringence than the first type and forms sheaf-like aggregates of flaky crystals. Unlike the first type of chlorite, the crystals are not replacements of plagioclase.

Very small crystals of an orange brown-green pleochroic mineral are intergrown with crystals of the first type of chlorite where they are extensively developed. Occasionally they also occur independently along cracks in the rock. This mineral has a higher birefringence than either serpentine or chlorite and is probably bowlingite or chlorophaeite (Deer, Howie and Zussman, 1962, i, p. 18).

Secondary magnetite is invariably present as trains of minute particles along the centres of the antigorite-filled cracks in the olivine crystals. It is also disseminated throughout the rocks, and in many of the dykes it forms rims around the olivine crystals. This magnetite appears to have been exsolved during the formation of serpentine and chlorite and can often be distinguished from opaque chrome spinel by its smaller grain-size and lack of crystal form.

Secondary carbonate is present in small amounts in some of the dykes, particularly associated with the patches of glass (chapter V.2.f).

Two minerals which are very rare in all the dykes except 31, where they form approximately 3% and 1% of the rock respectively, are a bluish-green monoclinic amphibole and epidote. The amphibole replaces pyroxene. It does not form rims but appears to replace the pyroxene mainly where it is in contact with one of the numerous small patches (described below) which occur throughout dyke 31. Consequently, one end of a pyroxene crystal may be totally transformed to amphibole whereas the other is perfectly fresh. The patches are between 3 mm and 1 cm in diameter and are composed mainly of amphibole, the second type of chlorite and magnetite. Olivine and chrome spinel also occur in these patches but crystals of the former are invariably pseudomorphed by serpentine. The minerals composing these patches may not be of secondary origin but may have been formed by late-stage magmatic crystallization of numerous small volatile-rich pockets in the dyke. The epidote also appears to occur mainly in these patches.

Minute flakes of biotite occasionally border the crystals of chrome spinel and, in some of the more altered dykes, barely perceptible crystals of sericite are developed along hairline fractures in the plagioclase.

Two cases of extensive alteration of olivine to minerals other than serpentine and chlorite have been observed. In the first the olivine is pseudomorphed by a greenish-yellow mineral with third order birefringence. It is non-pleochroic and tends to be fibrous. It may be talc (cf. Bowen, 1928, p. 151). In the second case the olivine is replaced by a very fine crystal aggregate which has imparted a dense clouding to the pseudomorphs. This aggregate may be composed of serpentine and magnetite.

h) Textures.

As the textures of the rocks depend to a large extent on the relative grain-sizes of the three principal minerals they vary from one dyke to another and usually within individual dykes. There are two distinct textural relationships in the dyke rocks: that between the pyroxene and the plagioclase and that between the olivine and the "groundmass". The principal variations of both are described below and the textures of each dyke are summarized in Table 7.

Where the "groundmass" is very coarse-grained the plagioclase crystals are sub-equant and larger than the pyroxene crystals which are, consequently, interstitial (Fig. 45). [The term interstitial is

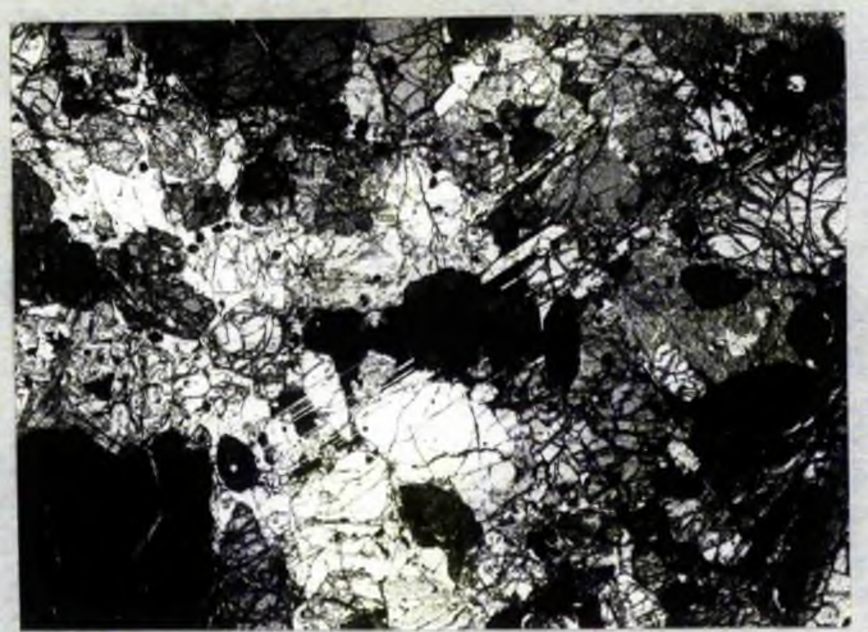

Fig. 45. Plagioclase and interstitial pyroxene poikilitically enclosing olivine crystals in the centre of dyke 1. X 15; crossed nicols.

used in preference to intersertal since the interstices between the plagioclase crystals are occupied by a single crystal rather than a mesostasis of glass and small crystals, (cf. Howell, 1957, p. 152)]. As the grain-size decreases the plagioclase tends to occur as elongate laths which are smaller in area than the co-existing pyroxene crystals and, in such cases, the pyroxene crystals are sub-ophitically intergrown with the plagioclase laths (Fig. 46). When small amounts of large, sub-equant crystals co-exist with laths (Fig. 47) sub-ophitic texture is developed rather than interstitial texture. Further decrease in the size of the plagioclase crystals does not produce any difference in texture.

Fig. 46. Porphyritic olivine crystals in a sub-ophitic groundmass near the margin of dyke 1. X 15; crossed nicols.

Fig. 47. Sub-ophitic texture near the margins of dyke 8. X 15; crossed nicols.

TABLE 7.

Petrographical Data for the Dykes.

DYKE	PART	OLIVINE Length of Crystals (mm) Maximum observed	OLIVINE Range of majority	PLAGIOCLASE Length of Crystals (mm) Maximum observed	PLAGIOCLASE Minimum observed	PLAGIOCLASE Range of majority	Habit of Crystals	PYROXENE Length of Crystals (mm) Maximum observed	PYROXENE Range of majority	TEXTURES Olivine/groundmass	TEXTURES Pyroxene/plagioclase
1	Centre	6	0.5-2	5	0.3	0.5-3	sub-equant.	2	0.5-1.5	poikilitic	interstitial
	Margin	7	0.5-1.5	2	0.1	0.5-1	laths > elongate laths > sub-equant.	1.5	0.3-1	porphyritic	sub-ophitic
2	Centre	8	0.5-1.5	2	0.1	0.5-1.5	sub-equant > laths.	2	0.5-1.5	porphyritic	sub-ophitic/interstitial
	Margin	3	0.5-1	1.75	0.1	0.2-0.5	elongate laths > laths > sub-equant.	0.5	0.2-0.5	porphyritic	sub-ophitic
3	Centre	3	0.5-1.5	4	0.3	0.5-3	sub-equant.	2	0.5-1.5	poikilitic	interstitial
	Margin	4	0.5-1.5	2	0.3	0.5-1.5	sub-equant > laths.	2	0.5-1.5	poikilitic	interstitial
6	Centre	See chapter V.2.i.		-	-	-	-			porphyritic	sub-ophitic
	Margin							-	-	porphyritic	sub-ophitic
8	Centre	4	0.5-1	2	0.1	0.3-1	laths > elongate laths > sub-equant.	1.5	0.5-1.5	porphyritic	sub-ophitic
	Margin	4	0.25-1	1	0.1	0.2-0.5	elongate laths > laths > sub-equant.	1	0.3-0.75	porphyritic	sub-ophitic
9	Centre	6	0.25-2	2	0.3	0.5-1.5	sub-equant > laths > elongate laths.	2.5	0.5-2	poikilitic	interstitial
	Margin	2	0.25-0.75	2	0.3	0.5-2	laths > sub-equant.	3	0.5-2	poikilitic	sub-ophitic/interstitial
10	Centre	4	0.5-2	0.75	0.1	0.3-0.75	elongate laths.	1.5	0.3-1	porphyritic	sub-variolitic
	Margin	3	0.5-1.5	0.75	0.1	0.3-0.5	elongate laths > laths.	0.5	0.2-0.5	porphyritic	sub-ophitic
11	Centre	3	0.5-2	3	0.3	0.5-1.5	sub-equant > laths.	4	0.5-3	poikilitic	interstitial
	Margin	3	0.5-2	a	a	a	a	a	a	poikilitic	sub-ophitic
12	Centre	3	0.5-1.5	a	a	a	a	a	a	porphyritic	interstitial
	Margin	3	0.5-1.5	a	a	a	a	a	a	porphyritic	sub-variolitic
13	Centre	13	0.1-2	1.5	0.1	0.3-1	laths > elongate laths > sub-equant.	1.5	0.3-1	porphyritic	sub-ophitic
	Margin	4	0.5-1.5	1	0.1	0.5-1	elongate laths > laths.	1	0.3-0.5	porphyritic	sub-variolitic
14	Centre	4	0.25-1.5	5	0.5	1-4	sub-equant.	3	0.5-2.5	poikilitic	interstitial
	Margin	-	-	-	-	-	-	-	-	-	-
15	Centre	4	0.5-1.5	3	0.1	0.5-1.5	laths.	3	0.5-2	porphyritic	sub-ophitic
	Margin	3	0.5-2	2	0.1	0.3-1	elongate laths and laths.	2	0.5-1.5	porphyritic	sub-ophitic
16	Centre	2	0.25-1	1	0.1	0.2-0.5	elongate laths > laths > sub-equant.	1	0.2-0.5	porphyritic	sub-ophitic
	Margin	4	0.25-1	1	0.1	0.2-0.5	elongate laths > laths > sub-equant.	0.5	0.1-0.3	porphyritic	sub-ophitic
18	Centre	4	0.25-1.5	3	0.2	0.5-1.5	sub-equant > laths.	2	0.5-1.5	poikilitic	sub-ophitic/interstitial
	Margin	2	0.25-1	1	0.2	0.3-0.75	laths.	1	0.2-0.5	porphyritic	sub-ophitic
20	Centre	8	0.5-2	a	a	a	a	a	a	porphyritic	sub-ophitic
	Margin	2	a	a	a	a	a	a	a	porphyritic	sub-ophitic/sub-variolitic
21	Centre	4	0.5-2	a	a	a	a	a	a	poikilitic	interstitial
	Margin	3	a	a	a	a	a	a	a	porphyritic	a
27	Centre	8	0.5-2	1	0.3	0.5-1	sub-equant and laths.	1.5	0.5-1	poikilitic	interstitial
	Margin	3	0.25-1.5	0.5	0.1	0.1-0.3	elongate laths > laths.	0.4	0.1-0.3	porphyritic	sub-ophitic
28	Centre	2	0.1-1	2	0.3	0.5-1	sub-equant.	1.5	0.5-1	poikilitic	interstitial
	Margin	5	0.25-1.5	2	0.3	0.5-1	sub-equant.	1.5	0.5-1	poikilitic	interstitial
29	Centre	5	0.25-1	1.5	0.1	0.5-1	laths > elongate laths.	1.5	0.3-1	porphyritic	sub-ophitic
	Margin	2	0.1-0.5	0.75	0.1	0.2-0.5	laths > elongate laths.	1.5	0.3-1	porphyritic	sub-ophitic
30	Centre	4	0.5-2	5	0.5	2-4	sub-equant.	3	1.5-3	poikilitic	interstitial
	Margin	3	0.5-2	8	2	2-4	sub-equant.	2	1.0-2	poikilitic	interstitial
31	Centre	2	0.5-1	5	0.5	1-3	sub-equant > laths.	4	1.0-3	poikilitic	interstitial
	Margin	2	0.5-1	5	0.5	1-3	sub-equant > laths.	4	1.0-3	poikilitic	interstitial
33	Centre	8	0.5-4	5	0.5	1-3	sub-equant > laths.	1	0.3-1	poikilitic	interstitial
	Margin	4	0.5-2	6	0.5	1-3	sub-equant > laths.	1	0.5-1	poikilitic	interstitial
34	Centre	7	0.5-2	4	0.3	0.5-2	sub-equant > laths.	1.5	0.5-1	poikilitic	interstitial
	Margin	3	0.5-2	1.75	0.1	0.3-1	elongate laths and laths.	1	0.5-1	porphyritic	sub-ophitic
35	Centre	3	0.5-2	a	a	a	? sub-equant.	a	a	poikilitic	interstitial
	Margin	3	a	a	a	a	a	a	a	porphyritic	a

NOTES.

i). a = property not determined due to alteration of the rock.

ii). tabulated specimens of dyke margins are less than 1 foot from the contact.

iii). Crystals larger than the observed maximum are almost certainly present. [As some of the olivine crystals are very large compared with the size of a normal thin section the sampling error is large.]

iv). 0.1 mm is given as a minimum crystal length as the exact size of smaller crystals is not readily determined.

v). Dyke 6 exhibits slight longitudinal variations and is described separately (chapter V.2.i).

vi). The contacts of dykes 3 and 14 are not exposed. The margins of dyke 14 are therefore omitted from the table but, as specimens from the south-west edge of outcrop 3/4 have characteristics suggesting that this edge is near the contact, they have been taken as representing the margins of dyke 3.

vii). Some of the dykes, especially 9 and 10, have varying marginal relations. The tabulated margin of dyke 9 is that in outcrop 9/4 (see below).

viii). The "ranges of majority" are visually estimated for comparison of the approximate grain-sizes.

ix). The distinction between laths and elongate laths is made at a length: breath ratio of 10:1.

In four of the dykes plagioclase laths occur in slightly radiating aggregates (Fig. 48) and the texture is sub-variolitic (Drever and Johnston, 1958, p. 484) rather than sub-ophitic.

Fig. 48. Sub-variolitic texture in the centre of dyke 10. X50; crossed nicols.

A gradational change in texture from interstitial in the centre of the dyke to sub-ophitic near the margins is common, e.g. dyke 1 (cf. Figs. 45 and 46).

The textural relationship between the olivine and the "groundmass" is governed mainly by the size of the plagioclase and pyroxene crystals. Where elongate plagioclase laths sub-ophitically intergrown with pyroxene crystals form the "groundmass" the olivine crystals are mostly larger than those of the pyroxene and plagioclase and the rock is porphyritic. Where the felspar and pyroxene crystals are large and sub-equant only a few of the olivine crystals are larger than these and the term porphyritic is not applicable. In such cases the majority of the olivine crystals are considerably smaller than the "groundmass" crystals and are often poikilitically enclosed by them (Fig. 45). As the "groundmass" grain-size of many of the dykes decreases towards the margins they have poikilitic centres and porphyritic margins, e.g. dyke 1 (Table 7).

In some of the more extensively altered rocks the original texture of the "groundmass" is obliterated.

No detectable "flow orientation" of plagioclase laths occurs in the dykes.

The textures of the dykes and the evidence they present of the conditions under which the dykes crystallized are discussed in chapter IV.

i) Longitudinal Variations.

Petrographically, most of the dykes are remarkably constant along their length but a few of them exhibit slight longitudinal variations. These are most evident in dyke 6, the longest of the dykes, in which there are two principal longitudinal variations. Firstly, the olivine content increases slightly from the north-west end of the dyke towards the south-east end. The size of the olivine crystals is relatively constant (maximum length = 4mm) throughout the dyke except in the margins near the north-west end where they are noticeably smaller (maximum length = 2mm).

Secondly, the sizes of the plagioclase and pyroxene crystals increase in the same direction as the olivine content, the maximum length of the plagioclase crystals in the centre of the dyke increasing from 1.5 mm to 3 mm and that of those in the margins increasing from 0.5 mm to 1.75 mm.

These variations are negligible in comparison with the transverse variations which occur within this and other dykes and, consequently, appear to be of little significance.

j) Comparative Petrography of Contacts.

The margins of many of the dykes differ in several respects from their centres (Table 7. etc.). These differences are invariably due to gradual changes in one or more of their textures, crystal sizes and mineral contents from the centre to the margin. The rates of these changes are not constant but are greatest near the contacts with the country rock. Consequently, where contacts are exposed (Table 4), the changes in the dyke rocks close to the contacts have been carefully studied.

The contacts with the country rocks are not uniform and seven different types [types (i) - (vii)] have been identified. Petrographic descriptions of examples of each of the types are presented below and the minor variations of the types are briefly described. Some of the dykes exhibit different types of contact at different points along their length, e.g. dykes 9 and 10, and these are listed under the appropriate type.

Type (i) contacts occur between dyke 1 and basalt. Both contacts are exposed in outcrop 1/2 and one has been sampled by drilling in outcrop 1/10 (chapter V.1.b). All three contacts are basically identical and, consequently, only that in outcrop 1/10 is described. Six inches from the contact the dyke rock is identical with the marginal rock described in Table 7 except that subequant plagioclase crystals are absent. It contains 45½% olivine crystals (cf. over 65% in the dyke centre) in a "groundmass" which is much finer-grained than that in the centre of the dyke. This rock persists to within one inch of the contact with only a slight decrease in the size of the plagioclase laths. Over the remaining inch to the contact the "groundmass" becomes much finer-grained (Fig. 49), the plagioclase laths decreasing to less than 0.3 mm in length. [Two inches inward from the contact they may be as long as 2 mm]. Olivine phenocrysts are present right to the contact where they form over one-third of the rock. This very fine-grained dyke rock is in contact with, but is not chilled against, slightly coarser-grained basalt (Fig. 49) composed of 14% small olivine phenocrysts in a "groundmass" of plagioclase laths ophitically intergrown with clinopyroxene. This rock is identical with a specimen of country rock obtained several yards away from the dyke. The plagioclase in this rock has a maximum extinction angle (in the zone perpendicular to (010)) of 41° compared with a corresponding

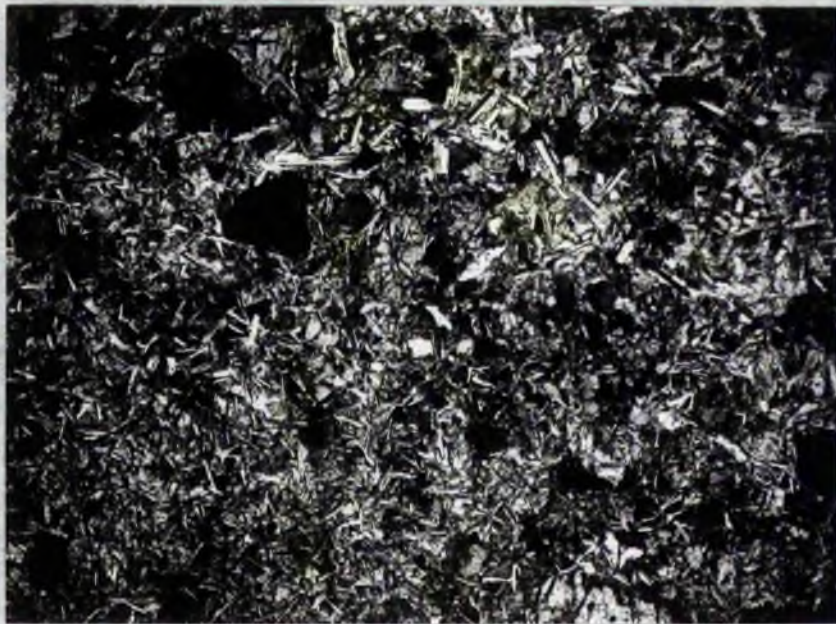

Fig. 49. Contact between dyke 1 and basalt.
X 15; crossed nicols.

value of $46\frac{1}{2}^{\circ}$ for the plagioclase in the dyke margins. It is undoubtedly olivine basalt of the Ophimottled Basalt group (Almond, 1964, map facing p. 234) although it differs slightly from the lavas of this group described by Almond (p. 417). This difference is probably due to local variation between individual flows. On a microscopic scale the contact is not planar, small veinlets of fine-grained dyke material penetrating the lava for a few millimetres. Along the contact is a very narrow zone in which both the dyke rock and the basalt are more extensively altered to secondary minerals. This zone is probably due to the relatively easy path provided by the contact for the agents of deuteric alteration.

In outcrop 27/3 dyke 27 intrudes medium/fine-grained gabbro and adjacent to the contact it is identical with the corresponding parts of dyke 1.

Approximately two inches in from the contacts of dyke 6 with medium/coarse-grained gabbro in outcrop 6/6 the dyke rock is similar to the marginal rock at the south-east end of the dyke (Table 7; chapter V.2.i). The grain-size of the "groundmass" decreases towards the contact until at the contact (Fig. 50) the plagioclase crystals are less than 0.4 mm. long. The rock at the contact is not so fine-grained as that at the contacts of dyke 1 and the plagioclase crystals are less acicular (cf. Figs. 49 and 50). As in dyke 1, olivine phenocrysts are abundant right to the edge of the dyke.

Occasional fine-grained offshoots from the dyke penetrate the gabbro, often for more than 5 mm, frequently encircling crystals in the gabbro. These narrow veinlets contain many small olivine crystals but very few large phenocrysts although these are abundant in the margins of the dyke. It appears that when the offshoots were formed, presumably during the emplacement of the dyke, the olivine had already crystallized and all but the smallest crystals became wedged in the entrances to the offshoots, thus permitting only the interstitial liquid

Fig. 50. N.E. contact between dyke 6 and gabbro in outcrop 6/6. X 15; crossed nicols.

to enter the veinlets. This liquid subsequently crystallized to a fine-grained plagioclase/pyroxene rock identical with the "groundmass" of the dyke rock at the contacts. Sometimes, where the entrance to one of the offshoots is exceptionally wide, olivine phenocrysts have been admitted for a short distance before becoming wedged (Fig. 50).

The south-west contact of dyke 9 in outcrop 9/2, the north contact of dyke 10 at the west end of outcrop 10/1 and the contacts of dyke 15 and dyke 27 in outcrop 27/1 are similar to those of dyke 6 in outcrop 6/6. The contacts of dyke 6 in outcrop 6/7 and dyke 18 are also similar to those in outcrop 6/6 but the size of the plagioclase crystals does not decrease so markedly towards the contact and a few sub-equant felspar crystals occur close to the contacts of dyke 6 in outcrop 6/7. The contact of dyke 30 with coarse-grained gabbro appears to be very sharp in the hand specimen, but in thin section it can be seen that, while olivine phenocrysts do not occur beyond the contact, the fine-grained "groundmass" material containing many small olivine crystals has invaded the gabbro for almost one inch, often breaking off small fragments. Apart from the more extensive penetration of the country rock by dyke material this contact is similar to those already described.

Type (ii) contacts occur between dyke 9 and gabbro in outcrops 9/1 and 9/3. Olivine phenocrysts are again present right to the edge of the dyke but the "groundmass" is as coarse-grained at the contacts with the gabbro as it is in the centre of the dyke (Fig. 51).

Type (iii) contacts occur between dyke 31 and eucrite. This type may be regarded as intermediate between types (i) and (ii). Olivine is abundant right to the unchilled contacts with the coarse-grained country rock. The grain-size of the "groundmass" decreases towards the edges of the dyke but even at the contacts it is not

Fig. 51. N.E. contact between dyke 9 and gabbro in outcrop 9/1. X 15; crossed nicols.

particularly fine-grained (Fig. 52). Plagioclase crystals, which are sub-equant and seldom less than 2 mm long in the dyke rock a few inches from the

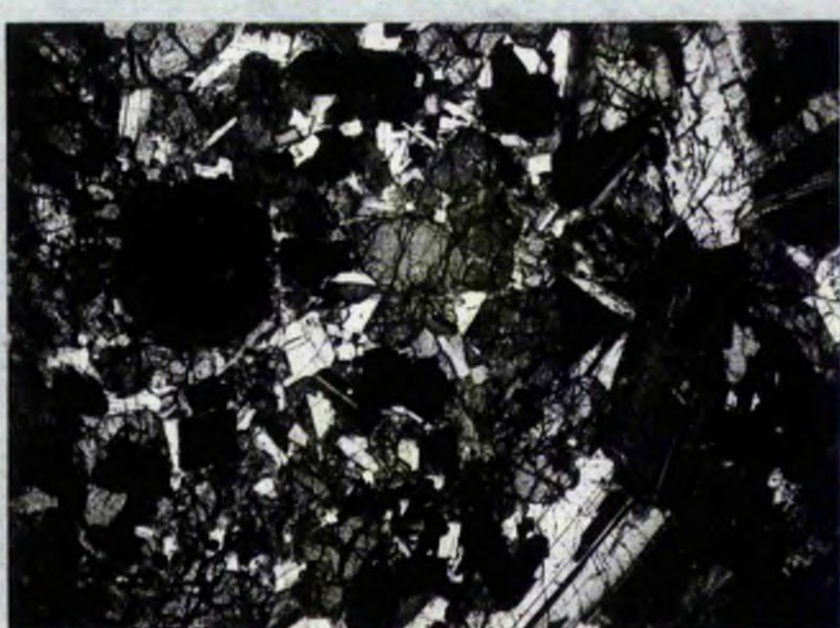

Fig. 52. W. contact of dyke 31 with eucrite. X 15; crossed nicols.

contact (Table 7), become smaller towards the edge of the dyke and at the contact broad laths over 0.5 mm long are dominant, although sub-equant forms are not uncommon.

Type (iv) contacts occur where dyke 10 intrudes medium/fine-grained basic rock. With the exception of that part of the north contact described under type (i) above the dyke has chilled selvedges. The selvedges are composed of abundant olivine phenocrysts in a groundmass which was originally tachylitic but is now partially devitrified to a cryptocrystalline granular aggregate. Inwards from the contact the groundmass becomes microcrystalline. Half an inch from the gabbro minute, acicular plagioclase crystals sub-ophitically intergrown with pyroxene are discernible. With increasing grain-size the contact rock grades inwards into the marginal rock described in Table 7. At one locality, on the south side of the dyke, the contact material penetrates the country rock for more than two feet, forming a breccia. This contact breccia was described by Bowen (1928, p. 154) who observed that olivines "have been carried........ only into the larger seams". The present writer's observations confirm this but indicate that large olivine crystals are almost universally present in the matrix of the breccia since very few of the seams are too small to have admitted them. A similar breccia is developed to a lesser extent on the north side of the dyke at the same locality.

Dyke 11 has a similar chilled selvedge although it intrudes coarse-grained gabbro, but no contact breccia has been observed. Unlike the "groundmass" texture of dyke 10, which passes inwards from cryptocrystalline to sub-ophitic and then to sub-variolitic, that of dyke 11 grades from cryptocrystalline to sub-variolitic to sub-ophitic.

In contacts of types (i) to (iv) olivine persists right to the edge of the dyke, although generally decreasing in amount, and the types differ mainly in the grain-size of the "groundmass" at the contact. In contacts of types (v) to (vii) (below) olivine phenocrysts are absent from the contact rocks.

Type (v) contacts are relatively uncommon. The north-east contact of dyke 9 in outcrop 9/4 is of this type. The plagioclase crystals in the marginal dyke rock one foot from the contact (Table 7) may be as long as 2 mm. The grain-size of the "groundmass" decreases towards the contact until two inches from the country rock the plagioclase laths are less than 0.75 mm long.

There is a corresponding decrease in the olivine content from over 35% to less than 20%. Within two inches of the contact olivine phenocrysts are very rare although very small olivine crystals do occur. Pyroxene, which is sub-ophitically intergrown with plagioclase where olivine is abundant, becomes increasingly granular towards the contact and the plagioclase laths become smaller. At the contact very fine-grained dyke rock is in unchilled contact with an even finer-grained, granular basic rock (Fig. 53). Where the contact of dyke 16 is exposed (Table 4) it is also of this type.

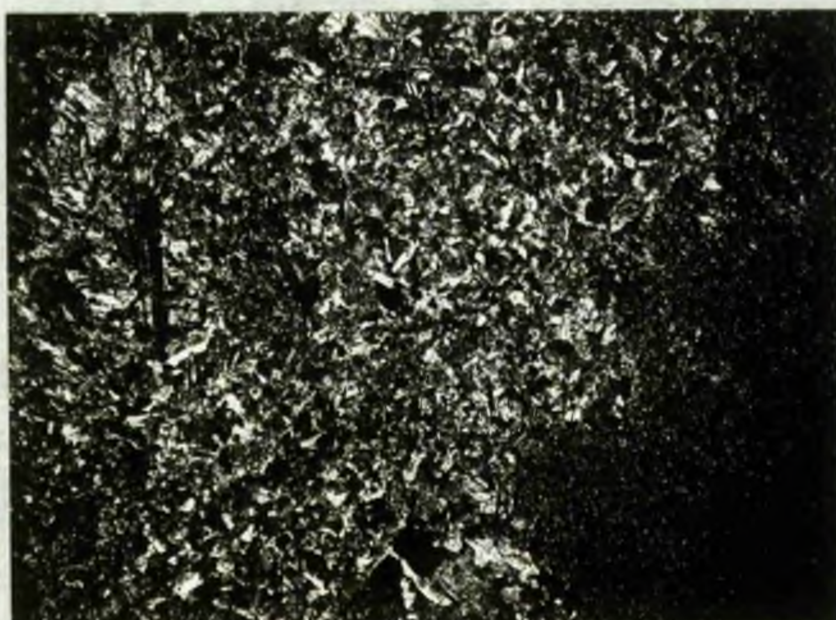

Fig. 53. N.E. contact of dyke 9 in outcrop 9/4. X 15; crossed nicols.

Type (vi) contacts occur where dyke 29 intrudes a plagiophyric basalt. The marginal rock described in Table 7 is six inches from the contact and contains over 20% olivine, mainly as small phenocrysts. This rock extends to within half an inch of the contacts with a gradual decrease in olivine content. Half an inch from the contacts with the basalt, olivine crystals are rare and the rock is mineralogically identical with the "groundmass" of the dyke rock six inches from the contact. The grain-size decreases appreciably over the marginal two inches of the dyke until at the unchilled contacts the plagioclase crystals are acicular and less than 0.3 mm long. The principal difference between this type of contact and type (v) is that the olivine content decreases very gradually to almost zero in type (vi) whereas this decrease is relatively rapid in type (v).

Type (vii) contacts occur only in dyke 33. Although this dyke is very narrow (Table 2) it is very coarse-grained (Table 7). The coarse-grained rock with sub-equant plagioclase crystals extends from the centre of the dyke to within 0.6 inches of the contacts. At 0.6 inches from the contacts the plagioclase crystals become lath-shaped and begin to decrease in size towards the edges of the dyke. Approximately

0.3 inches from the contacts the felspars are acicular and very small. This fine-grained rock is in unchilled contact with coarse-grained gabbro (Fig. 54). Olivine phenocrysts are abundant in the central part of the dyke and decrease slightly in amount towards the margins. 0.4 inches from the contacts olivine crystals become very rare but less than 0.15 inches from the contact small crystals of olivine are again plentiful. At the contact the olivine crystals are small and granular (Fig. 54).

Fig. 54. N. contact of dyke 33. X 15; crossed nicols.

The three types of contact recognised by Bowen (1928, p. 150) correspond approximately to types (i), (ii) and (vi).

3. THERMAL METAMORPHISM.

The contact metamorphic effects of the dykes upon the rocks they intrude have not been extensively studied but there appears to be little doubt that moderate thermal metamorphism has occurred in some cases. There is no evidence of intense thermal metamorphism similar to that recorded where ultrabasic minor intrusions intrude sedimentary rocks (Drever and Johnston, 1958, p. 475; Wyllie, 1961). The metamorphism of basalt by dyke 1 and of gabbro by dyke 6 are briefly described.

Secondary minerals are abundant in the lavas adjacent to dyke 1: olivine is partially or completely altered to bowlingite or antigorite and plagioclase crystals are often partially replaced by aggregates of minute chlorite and clinozoisite crystals. However, these secondary minerals are common throughout the lavas and their presence cannot, therefore, be attributed to contact metamorphism by the dyke magma. According to Almond (1964, p. 416 and 419) they are due to low-grade thermal metamorphism of the lavas by the gabbro of the Blaven Range, i.e. the Inner Layered Gabbro of Weedon (1961, fig. 1).

In outcrop 1/2 the dyke intrudes amygdaloidal basalt. Amygdales several millimetres in diameter filled with carbonates and zeolites are abundant in the basalt but decrease in size and number towards the dyke and are absent close to the dyke. This effect can be attributed to contact metamorphism by the dyke magma. The width of the amygdale-free zone is subject to considerable local variation, ranging from over 1 foot to less than 6 inches. Whatever the nature of the metamorphic processes which led to the disappearance of the amygdales from the lava, they must have been of a higher grade than the metamorphism by the Inner Layered Gabbro since this did not affect the amygdales. The absence of other relatively high-grade contact metamorphic effects, which must have accompanied the removal of the amygdales, can be attributed to their having been obscured by the low-grade metamorphism of the Strathaird lavas by the Inner Layered Gabbro. This implies that the emplacement of the dyke preceded that of the Inner Layered Gabbro (see chapter XVI). Although this hypothesis is based solely on the absence of amygdales from the basalt immediately adjacent to the dyke, the fact that most of the secondary minerals developed in the lavas also occur in the dyke is consistent with the suggestion that the general metamorphism post-dated the intrusion of the dyke.

Minor differences exist between the gabbro in contact with dyke 6 (outcrops 6/6 and 6/7) and that several feet from the dyke. The pyroxene of the contact gabbro is sometimes slightly clouded and the crystals frequently show peripheral alteration to a pleochroic green amphibole (hornblende). Some of the smaller crystals are completely replaced by the amphibole. Very occasionally pyroxene crystals close to the contact have been replaced by a matrix of carbonate containing relict pyroxene and crystals of a tremolitic amphibole. The olivine of the gabbro in contact with the dyke is extensively altered and exsolved iron oxide is concentrated along the cleavage planes. Minute grains, tentatively identified as clinozoisite and sericite, occur in the plagioclase crystals. These inclusions occasionally occur in patches or concentrated along cracks but they occur most commonly in narrow zones sub-parallel to, and just within, the crystal edges (Fig. 55).

Fig. 55. Alteration zones within felspar crystals in the gabbro adjacent to dyke 6. X 50; crossed nicols.

Patches of chlorite are common and near the contacts with the dyke epidote is occasionally present. The above effects decrease away from the dyke and six inches from the contacts most of them are negligible. Similar phenomena have also been observed in gabbro near the contacts with some of the other dykes. These effects appear to be results of low-grade thermal metamorphism of the gabbros by the dykes but without a detailed study of the Cuillin gabbros the possibility of an alternative cause cannot be entirely eliminated.

VI. VARIATIONS IN PRIMARY MINERAL CONTENTS.

1. DETERMINATIVE METHODS.

The relative amounts of the three principal minerals have been found to vary across all the dykes studied in detail. This transverse variation is greater in some of the dykes than in others and representative examples of the dykes, in which secondary minerals are not extensively developed, have been selected for quantitative studies of these variations.

Serial collections were made across these dykes, sometimes at more than one locality, and the amounts of the primary minerals in each of the specimens were determined by modal analysis. The olivine, pyroxene and plagioclase crystals in a single specimen often differ considerably in size and, unless a separate analysis is made for each mineral, the analytical technique must be such as to give satisfactory results for all three minerals. In addition, the size ranges of the crystals of each of the minerals vary within a dyke and from one dyke to another. Under these circumstances the most accurate analysis for each specimen would be obtained by adjusting the grid spacing, number of points counted and the area covered to the most suitable values for that specimen. However, such a technique cannot be employed since varying these parameters affects the validity of direct comparison of the results from different specimens. Before the method used here was selected it was carefully checked to verify that it gave accurate results for all three minerals under the different grain-size conditions encountered in the dykes.

A Swift electric point counter and automatic stage with a grid spacing of 0.3 mm x 0.1 mm were used to count 3,000 to 4,000 points covering an area greater than 100 sq. mm. First approximations to the variances for each mineral in rocks of different grain-sizes were obtained using the formula given by Solomon (1963) and the results indicate that the method is suitable for the dyke rocks. The method was also tested experimentally for both fine and coarse-grained dyke rocks. More than 20,000 points were counted over several thin sections of a sample of each type. The results of each successive 1,000 2,000, 3,000, 4,000, and 5,000 points were compared with the final result. It was found that the agreement between a particular result and the final result increased significantly with the number of points counted up to 3,000 points but when larger numbers of points were counted the further increase in agreement was slight. It was also observed that the differences between results for different thin sections of the same specimen were negligible. When the counted area included an exceptionally large olivine crystal, i.e. over 1 cm long, the result for 1,000 points had a high deviation and even that for 3,000 points had a slightly higher deviation than normal. Consequently, areas of a thin section containing an olivine crystal more than 7.5 mm long were deliberately avoided during modal analysis.

A grid spacing of 0.3 mm x 0.3 mm gave equally good results for the coarse-grained rocks but gave a slightly higher standard deviation for those in which the pyroxene and plagioclase crystals are smaller. Consequently, the 0.3 mm x 0.1 mm grid spacing was used throughout as described above.

The most significant variation is in the amount of olivine and, for some of the dykes, only this variation has been determined. With three notable exceptions, secondary minerals have been counted as such. The antigorite filling the cracks in the olivine and the serpentine/chlorite alteration at the margins of the olivine crystals, where it occurs within a rim of secondary magnetite, have been counted along with olivine since they were undoubtedly formed from it. Secondary magnetite has been included in the count of chrome-spinel due to the difficulty of discriminating between opaque minerals during modal analysis. Secondary magnetite generally forms less than one fifth of the "chrome-spinel" content.

The cognate xenoliths are often difficult to distinguish from the dyke rock in thin section but every possible precaution was taken to ensure the exclusion of xenoliths from the counted areas.

The results for the selected dykes are presented in the following section.

2. MINERAL DISTRIBUTIONS.

a) Dyke 1.

Serial collections were made across dyke 1 at two localities as far apart as possible along the exposed length of the dyke. The sampled outcrops are 1/2 and 1/10. The modal analyses of the specimens from outcrop 1/2 are given in Table 8. The olivine, plagioclase and pyroxene contents of the specimens are plotted against their position in the dyke in Fig. 56.

TABLE 8.

Modal analyses of specimens
from dyke 1 (outcrop 1/2)

Distance from the S.W. contact Ft.	Ins.	% Olivine + serpentine	% Pyroxene	% Plagioclase	% Chrome Spinel	% Secondary Minerals
0	6	31.1	31.7	31.3	2.2	3.8
0	11½	43.4	22.7	27.3	2.5	4.1
1	6	41.5	21.7	30.8	1.9	4.1
2	0½	44.4	19.7	30.4	1.8	3.7
2	3½	47.5	19.8	28.5	2.0	2.2
2	8½	48.1	20.1	28.5	1.7	1.5
2	11½	55.2	12.9	29.2	1.1	1.6
3	4½	56.4	12.9	29.4	0.8	0.7
4	4	62.5	9.7	21.1	1.3	5.7
4	8½	65.4	8.0	20.8	1.5	4.4
6	5	63.7	10.9	19.8	1.6	4.2
7	0	66.0	10.9	18.0	1.1	4.1
8	0½	66.8	10.3	17.4	1.4	4.3
8	8½	70.3	9.3	16.3	1.2	2.7
10	11½	68.3	8.9	18.2	1.1	3.6
12	2	66.5	9.8	19.9	1.3	2.6
20	3½	65.6	8.8	16.1	1.2	8.3
21	6	63.5	11.0	20.3	1.7	3.5
22	9	59.3	9.5	26.8	1.1	3.4
24	3	55.5	11.9	28.5	1.4	2.7
25	6	48.3	16.8	28.4	1.5	4.9
26	10½	46.2	19.8	29.4	2.3	2.2
27	5	47.4	18.3	28.7	1.3	4.3
28	3½	47.1	19.1	28.5	1.9	3.5
28	9½	45.1	19.7	30.3	1.3	3.6
30	1½	44.5	22.4	29.5	2.0	1.7

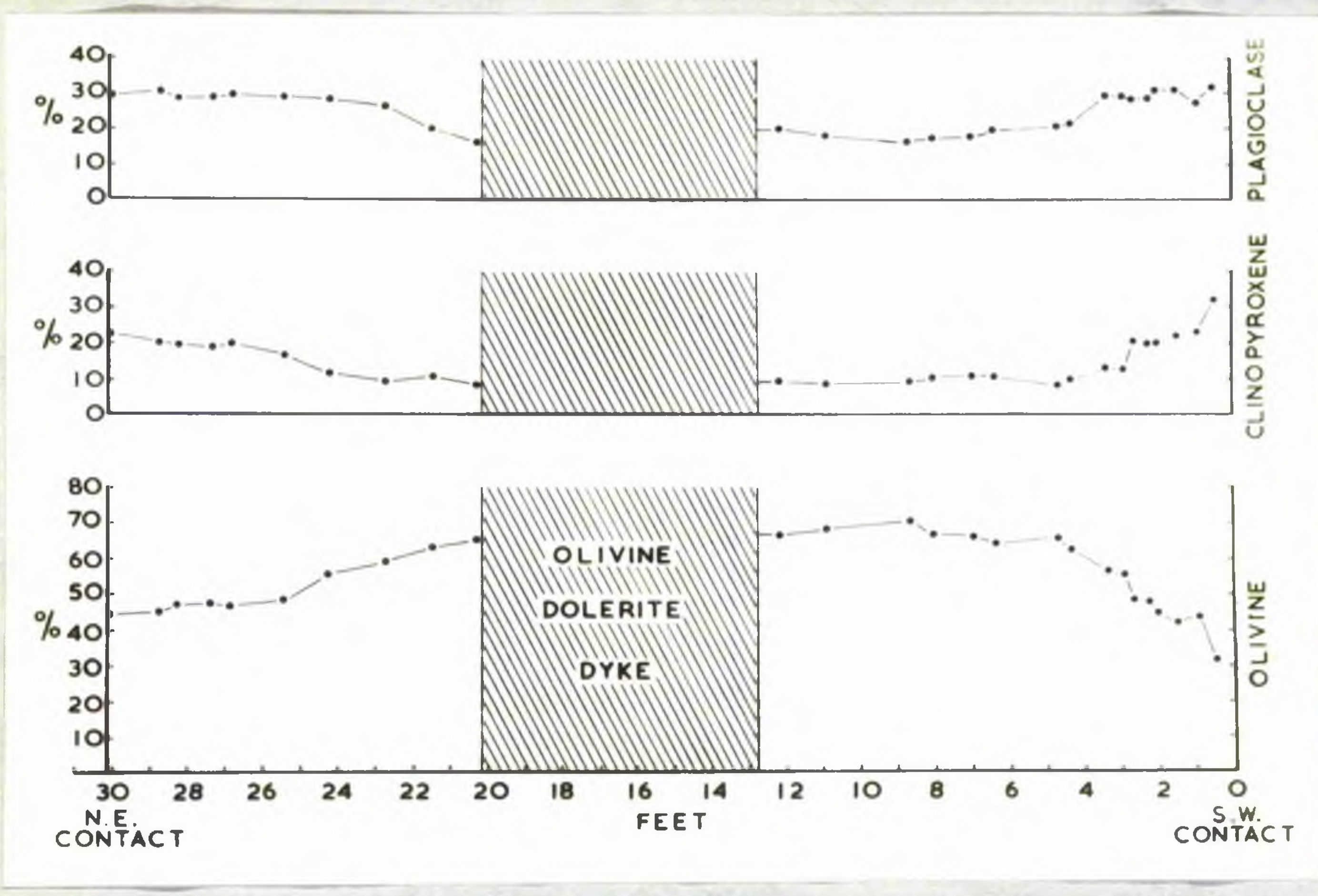

Fig. 56. Distribution of olivine, pyroxene and plagioclase across dyke 1 in outcrop 1/2.

The plots of the olivine, pyroxene and plagioclase contents (Fig. 56) approximate to smooth curves but many of the plotted points lie slightly off these. As the deviations of these points from smooth curves are less than the theoretical standard deviations for the modal analyses they are almost certainly due to the combined sampling and counting errors. Some of the analyses show relatively high contents of secondary minerals (e.g. Table 8, 20 ft. 3½ inches) and, theoretically the contents of olivine, pyroxene and plagioclase plotted in distribution diagrams such as Fig. 56 should be corrected for the alteration to secondary minerals. However, it is evident from examination of thin sections that some of the primary minerals alter more readily than others. Consequently, any attempt at such a correction, based on the assumption that the amounts of secondary minerals derived from each of the primary minerals are proportional to the amount of the primary mineral, would tend to distort, rather than improve the accuracy of the original distribution curves.

The distribution curves exhibit variations across the dyke which are of such magnitude as to be beyond the limits of determinative error.

Across dyke 1 in outcrop 1/2 the largest variation is in the olivine content. At the south-west edge of the dyke olivine forms only 31% of the rock. Away from this edge the olivine content increases rapidly and four feet from the contact the dyke rock contains more than 60% olivine. From there across the central part of the dyke the olivine distribution curve is much flatter. On the north-east side of the seven foot wide basic dyke which cuts the outcrop longitudinally (chapter V.1.c) the olivine content of the dyke decreases. The slope of the distribution curve at this side of the dyke is not as steep as that at the south-west side.

The plagioclase and pyroxene distributions vary antipathetically with the olivine distribution but the plagioclase:pyroxene ratio is not constant. Although the pyroxene and plagioclase distribution curves are very similar in shape the major changes in pyroxene content occur slightly nearer to the edges of the dyke than those in plagioclase content. All three mineral distribution curves are slightly asymmetrical with respect to the centre of the dyke.

The distributions of olivine, pyroxene and plagioclase across dyke 1 in outcrop 1/10 are given in Fig. 57 and the modal analyses of the specimens are presented in Table 9.

TABLE 9

Modal analyses of specimens from dyke 1 (outcrop 1/10).

Distance from N.E. contact Ft.	Ins.	% Olivine + serpentine	% Pyroxene	% Plagioclase	% Chrome Spinel	% Secondary Minerals
0	0¼	33.4	-	-	-	-
0	1	45.5	20.7	29.8	1.7	2.2
0	2	45.7	19.5	32.3	1.2	1.6
0	7½	46.0	19.5	31.2	1.4	2.0
1	1	43.4	18.1	33.8	1.6	2.9
1	11½	44.7	16.1	35.2	1.0	3.0
2	1	44.4	17.5	34.1	1.1	2.8
2	4	46.1	18.4	30.7	1.6	3.1
2	11	52.0	15.5	28.1	1.0	3.5
3	7	53.0	13.5	28.5	1.5	3.5
4	1	56.7	13.6	24.5	0.9	4.2
4	8	61.4	13.6	19.8	1.1	4.1
5	9	62.1	9.0	23.2	0.7	5.0
6	7	68.2	7.8	19.9	1.0	3.2
7	1	68.1	-	-	-	-
9	1	67.5	7.8	20.3	0.9	3.6
11	1	66.3	6.7	23.2	1.6	2.2
13	1	65.1	9.0	17.7	0.8	7.3
14	1	65.0	10.8	19.8	1.8	2.7
15	1	68.9	10.6	17.8	1.4	1.3
17	1	67.5	8.3	19.9	1.1	3.3
19	1	67.8	8.3	17.5	1.6	4.7
20	1	69.2	9.7	17.0	2.0	2.2
21	1	71.8	6.1	17.0	2.7	2.5
22	1	72.2	6.7	16.4	2.8	2.0
23	1	62.6	11.7	21.9	1.8	2.1
25	7	54.8	15.9	25.9	1.2	2.2
26	1	53.3	15.5	27.0	1.3	2.8
27	9	53.0	14.8	28.1	1.5	2.8

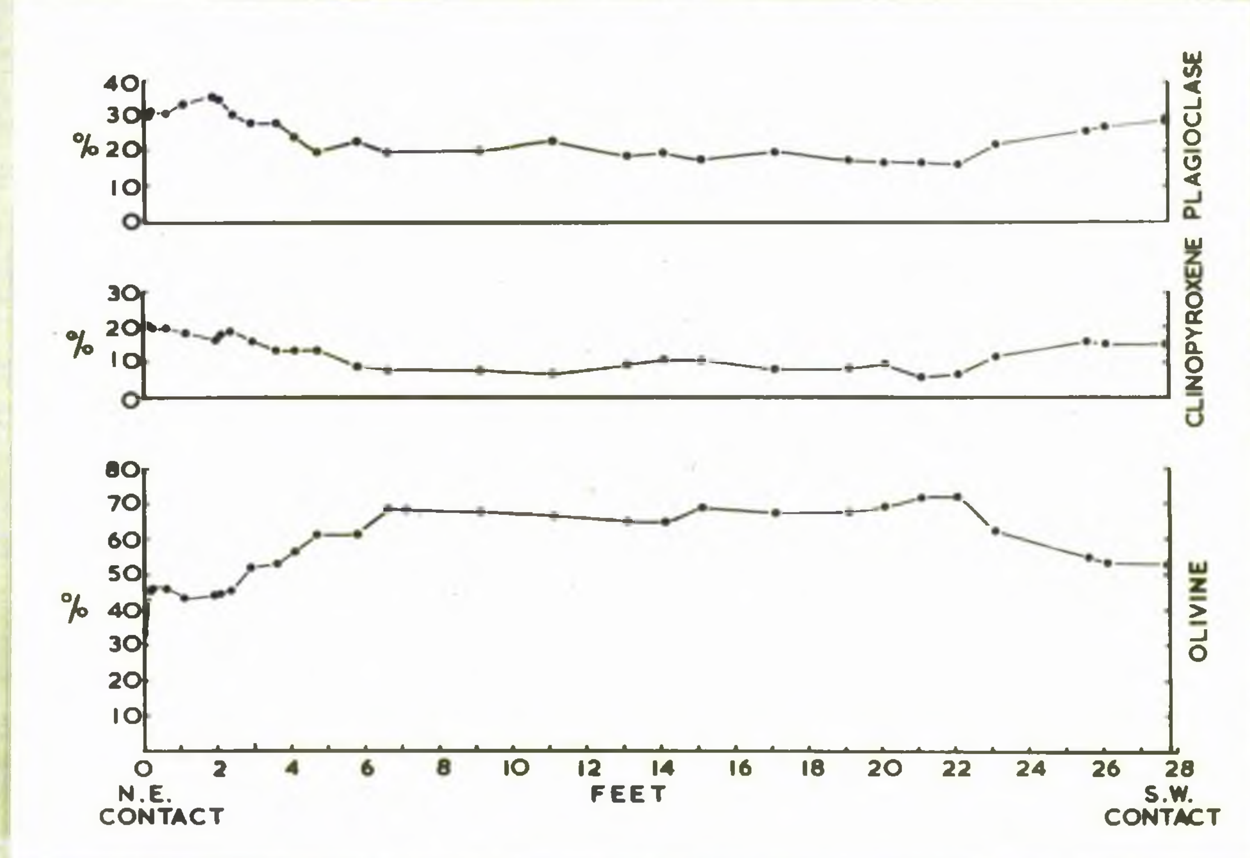

Fig. 57. Distributions of olivine, pyroxene and plagioclase across dyke 1 in outcrop 1/10.

The olivine distribution curve for dyke 1 (outcrop 1/10) is basically similar to that for outcrop 1/2, but in the central part of the dyke in outcrop 1/10 the curve is slightly bimodal. [The curve for outcrop 1/2 may also be bimodal with the north-east maximum now replaced by the basic dyke]. As in outcrop 1/2, the pyroxene and plagioclase contents of the dyke are inversely proportional to the olivine content, but in outcrop 1/10 the major changes in both occur at approximately the same distances from the contacts.

b) Dyke 2.

Transverse modal profiles (Fig. 58) have been prepared for dyke 2 (outcrop 2/1) but, although this outcrop presents the best cross-section available, the profiles are incomplete since neither contact is exposed. The modal analyses of specimens from this outcrop are given in Table 10. [Since the contacts are not exposed the positions of the specimens are given in relation to the exposure of country rock nearest to the south-west margin of the dyke].

TABLE 10

Modal analyses of specimens
from dyke 2 (outcrop 2/1)

Distance from country rock (S.W. side) Ft.	Ins.	% Olivine + serpentine	% Pyroxene	% Plagioclase	% Chrome Spinel	% Secondary Minerals
0	4	55.6	23.3	16.1	1.7	3.4
0	8½	49.7	20.5	26.2	2.4	1.3
1	1	47.8	16.4	33.0	1.3	1.5
1	9	46.2	17.6	32.3	2.1	1.9
2	4	50.0	17.2	29.2	1.5	2.2
3	0	51.7	15.5	29.0	1.6	2.2
4	1	47.6	14.9	32.6	1.9	3.2
4	6	49.8	13.3	35.0	1.2	0.8
5	11	48.0	14.9	32.4	1.7	3.1
8	2	49.8	15.8	31.6	1.8	1.1
8	7	52.1	13.7	30.8	1.5	2.0
10	1	48.1	14.3	33.8	1.8	2.0
10	7	46.9	14.2	35.7	1.5	1.9
11	3	45.9	15.9	34.7	1.8	1.9
12	1	44.0	20.2	30.9	1.8	3.2

In the central part of the dyke the olivine distribution curve is slightly bimodal. In this respect it resembles that for dyke 1 (outcrop 1/10) but the olivine content is 10% less than in the centre of dyke 1. Towards the south-west contact the olivine content decreases

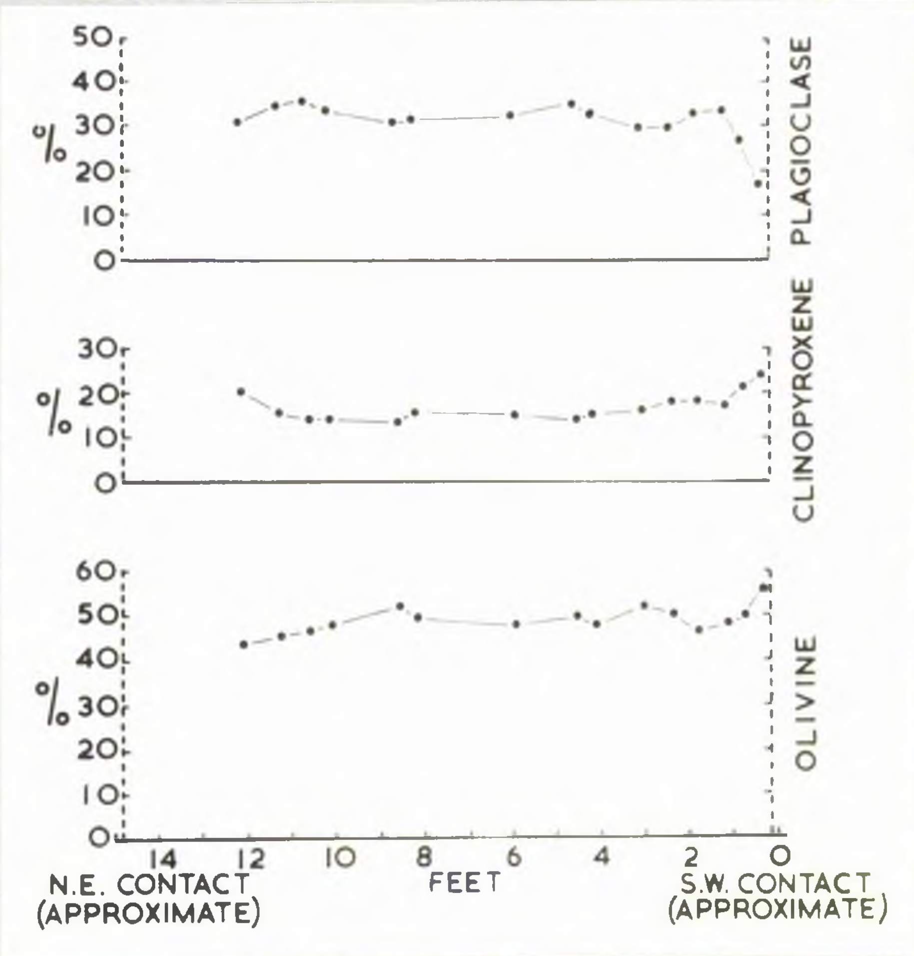

Fig. 58. Distribution of olivine, pyroxene and plagioclase across dyke 2 in outcrop 2/1.

slightly before increasing to reach a maximum for the dyke in the specimen obtained nearest to the country rock. A similar increase has not been observed at the north-east side of the dyke since no specimens were obtained from near the contact, but it appears probable from the distribution curve that such an increase does occur.

The pyroxene content varies antipathetically with the olivine content except near the south-west edge (and probably the unobserved north-east edge) where both increase. The pyroxene and plagioclase distribution curves are similar except near the south-west margin where the plagioclase content decreases. The change in the plagioclase content in the opposite sense to that in the pyroxene content is anomalous and the reason for this anomaly is discussed below (chapter XI.3). As in dyke 1, the plagioclase: pyroxene ratio in the central part of the dyke is approximately 2:1.

c) Dyke 6.

Transverse modal profiles have been prepared for dyke 6 in outcrops 6/6 and 6/7. The olivine contents of the specimens from outcrop 6/6 are presented in Table 11 and the corresponding distribution curve in Fig. 59. The distribution curve is bimodal and the olivine contents of the margins are more than 10% lower than that of the dyke centre. The curve is not symmetrical about the centre of the dyke:

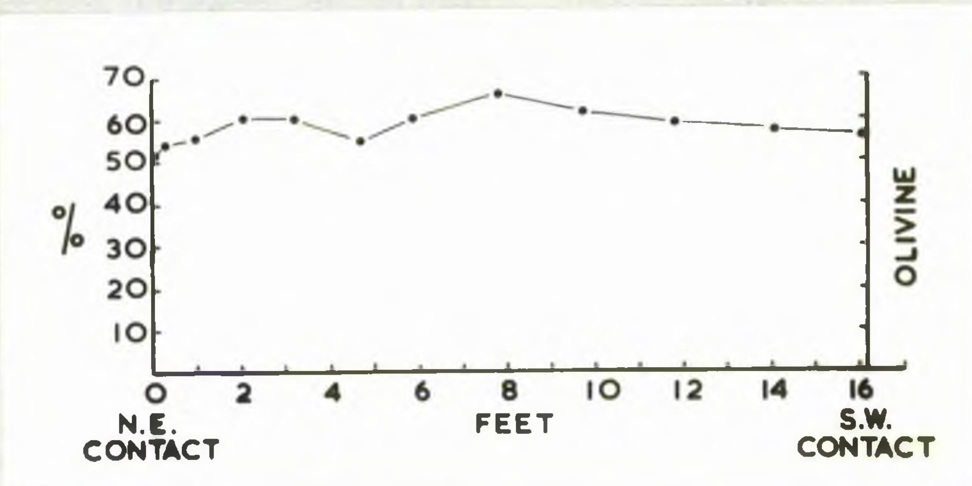

Fig. 59. Distribution of olivine across dyke 6 in outcrop 6/6.

TABLE 11

Olivine contents of specimens
from dyke 6 (outcrop 6/6)

Distance from N.E. contact Ft.	Ins.	% Olivine	% Serpentine and altered olivine	Total % originally olivine
0	$0\frac{1}{2}$	46.5	4.5	51.1
0	4	48.5	5.5	54.0
1	0	51.4	4.0	55.4
2	1	58.4	1.8	60.2
3	3	54.8	5.2	60.0
4	9	48.3	6.5	54.8
5	11	58.2	1.6	59.8
7	10	60.7	4.8	65.5
9	9	58.3	2.9	61.2
11	10	50.1	8.6	58.6
14	1	50.8	6.0	56.8
16	1	52.2	3.0	55.2

one of the maxima occurs almost at the centre and the other is three feet from the north-east contact.

The olivine content of the dyke in outcrop 6/7 (Fig. 60; Table 12) varies in a similar fashion to that in outcrop 6/6. The distribution curve is bimodal with one of the maxima at the centre of the dyke. The second maximum is again in the north-east half of the dyke but it is proportionally much closer to the first than in outcrop 6/6. The maximum olivine contents of the dyke in both outcrops are almost identical and the olivine contents of the margins of the dyke in outcrop 6/7 are very similar to the corresponding values for outcrop 6/6. Consequently, the slopes of the olivine distribution curve for the dyke in outcrop 6/7 are steeper than those in outcrop 6/6.

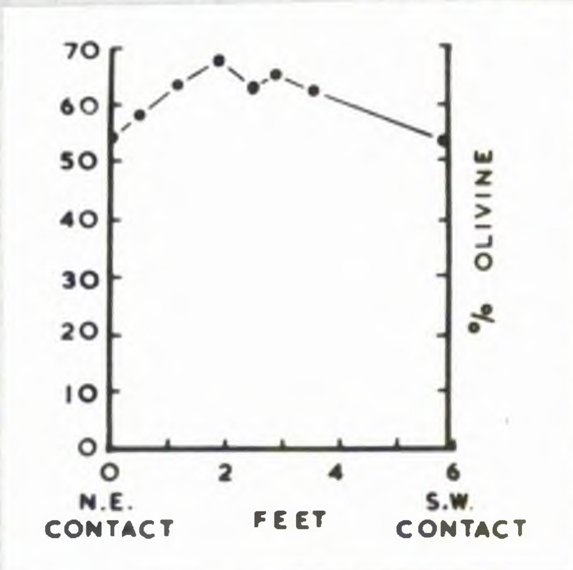

Fig. 60. Distribution of olivine across dyke 6 in outcrop 6/7.

TABLE 12

Olivine contents of specimens from dyke 6 (outcrop 6/7)

Distance from N.E. contact Ft.	Ins.	% Olivine	% Serpentine and altered olivine	Total % originally olivine
0	0½	52.3	1.4	53.7
0	6	54.6	2.7	57.3
1	2	61.5	1.4	62.9
1	11	64.7	2.5	67.2
2	6	58.1	4.3	62.4
2	11	61.0	3.5	64.5
3	7	57.2	4.7	61.9
5	10	46.7	6.3	53.0

d) Dyke 9.

The south-west contact of dyke 9 is not exposed in outcrop 9/4 but, since this is the only wide outcrop of dyke 9 which is otherwise adequately exposed, it has been selected. Consequently, the modal profiles prepared for this outcrop (Fig. 61) represent only a part of the dyke. From the widths of the dyke in other outcrops, particularly the north-west end of 9/1, it appears that the exposed part of the dyke in outcrop 9/4 is between a half and two-thirds of the complete width of the dyke. The modal analyses on which the transverse profiles are based are presented in Table 13.

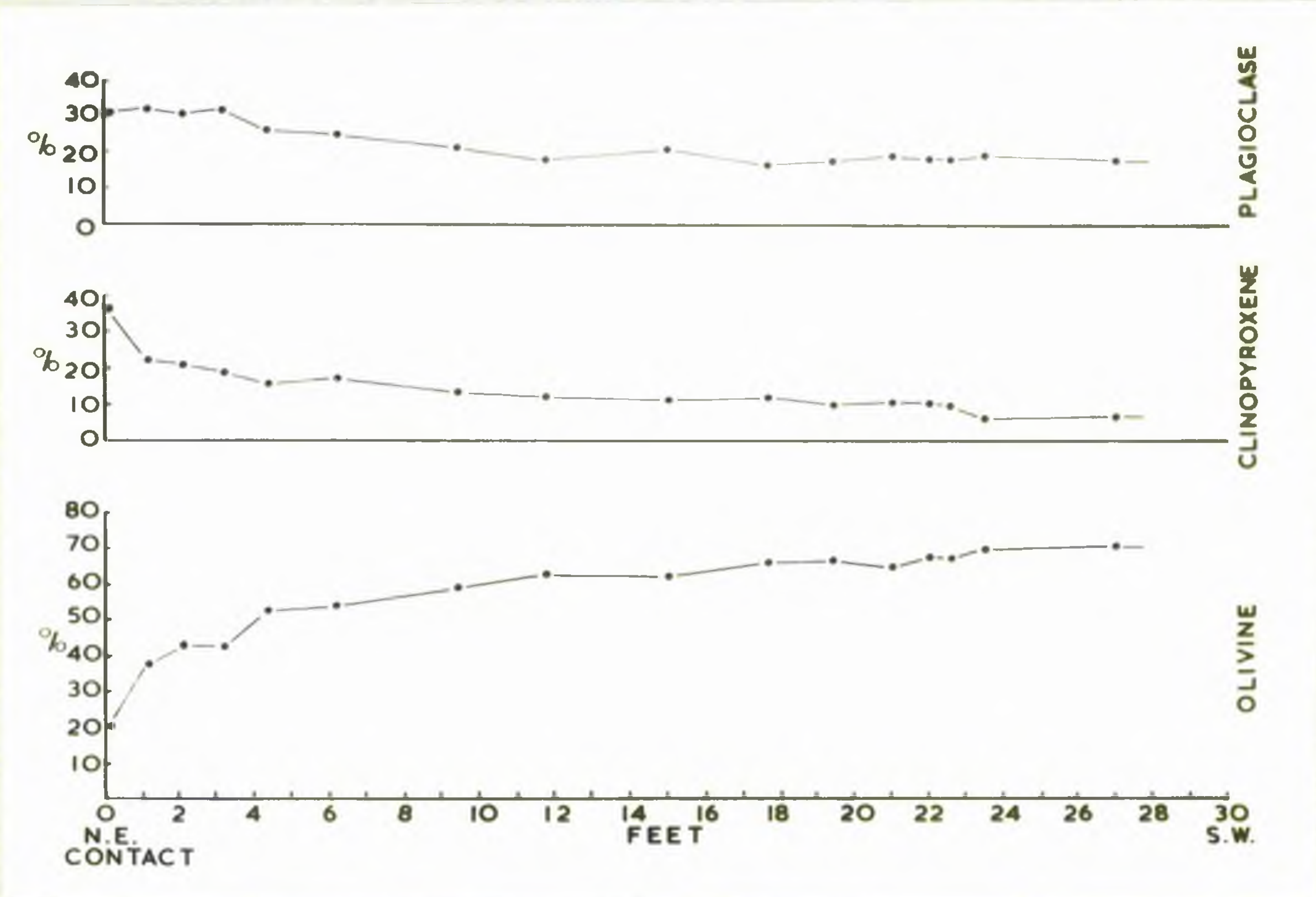

Fig. 61. Distributions of olivine, pyroxene and plagioclase across dyke 9 in outcrop 9/4.

TABLE 13

Modal analyses of specimens from dyke 9 (outcrop 9/4)

Distance from N.E. contact Ft.	Ins.	% Olivine + serpentine	% Pyroxene	% Plagioclase	% Chrome Spinel	% Secondary Minerals
0	2	20.0	36.3	31.3	4.2	8.2
1	2	37.5	22.2	32.1	2.7	5.5
2	1	42.4	21.0	31.0	2.0	3.7
3	2	42.4	18.9	32.0	1.6	5.1
4	4	52.5	16.0	26.3	1.8	3.5
6	2	53.8	17.2	25.1	1.5	2.2
9	5	58.9	13.5	21.7	1.5	4.5
11	9	62.8	12.3	18.5	2.2	4.3
15	0	62.1	11.1	21.1	2.1	3.7
17	8	65.7	12.0	17.0	1.5	3.9
19	5	66.7	10.0	18.1	1.3	4.0
21	0	64.8	10.7	19.4	1.5	3.7
22	0	67.8	10.1	18.8	1.0	2.4
22	7	66.2	9.8	18.6	1.1	4.4
23	6	69.6	6.0	19.8	1.3	3.4
27	0	70.4	6.6	18.3	1.2	3.3

The olivine content increases from the north-east edge of the dyke towards the centre. Over the marginal eight feet of the dyke this increase is relatively rapid, the olivine content changing from 20% to 60%, but in the remaining exposed part of the dyke the olivine content increases by less than 10% in twenty feet. There are corresponding decreases in the plagioclase and pyroxene contents towards the centre of the dyke. The primary mineral distribution curves are very similar to those for one half of dyke 1 in outcrop 1/2 (Fig. 56). This appears to confirm the above observation that approximately half the dyke is exposed, although it is possible that the distribution curves for the complete cross section are exceptionally asymmetrical.

e) Dyke 29.

The distribution of olivine across dyke 29 at a locality where the dyke is only $2\frac{1}{2}$ feet wide is given in Fig. 62. The corresponding modal analyses are presented in Table 14.

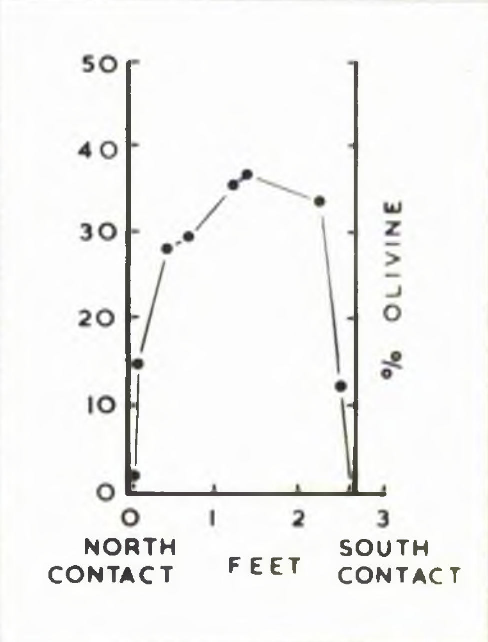

Fig. 62. Distribution of olivine across dyke 29 in outcrop 29/1.

TABLE 14
Olivine contents of specimens from dyke 29 (outcrop 29/1)

Distance from N. contact Ft.	Ins.	% Olivine + Serpentine
0	$0\frac{1}{4}$	Trace
0	$0\frac{1}{2}$	2.3
0	$1\frac{1}{2}$	14.9
0	$5\frac{1}{2}$	28.2
0	$8\frac{1}{2}$	29.7
1	3	35.6
1	5	36.8
2	3	33.7
2	6	12.5
2	$7\frac{1}{2}$	Trace

The plot of olivine content against the position in the dyke produces a relatively simple type of distribution curve. The centre of the dyke contains approximately 40% olivine and this amount decreases away from the centre until half an inch from the contacts the rock is virtually olivine-free (chapter V.2.j).

f) Dyke 31.

The olivine contents of a series of specimens collected across this dyke are given in Table 15 and are plotted in the usual way in Fig. 63.

The distribution curve has a maximum lying slightly to one side of the axis of the dyke. From this maximum the olivine content decreases towards both contacts passing through minima before increasing again. At the contacts the dyke contains only 5% less olivine than in the centre.

TABLE 15

Olivine contents of specimens
from dyke 31 (outcrop 31/2)

Distance from E. contact. Ft.	Ins.	% Olivine	% Serpentine and altered olivine	Total % originally olivine
0	1½	22.2	16.8	39.8
0	3	21.7	15.6	37.3
0	9	13.1	22.8	35.9
2	6	15.4	17.5	32.9
3	4	17.7	19.5	37.2
4	2	25.2	14.1	39.3
4	6	22.3	17.9	40.2
5	3	22.1	18.1	40.2
6	5	29.3	15.8	45.1
7	11	29.3	12.8	42.1
8	6	25.4	14.9	40.3
9	2	18.4	16.8	35.2
9	9	21.7	14.6	36.3
9	11½	25.6	15.0	40.6

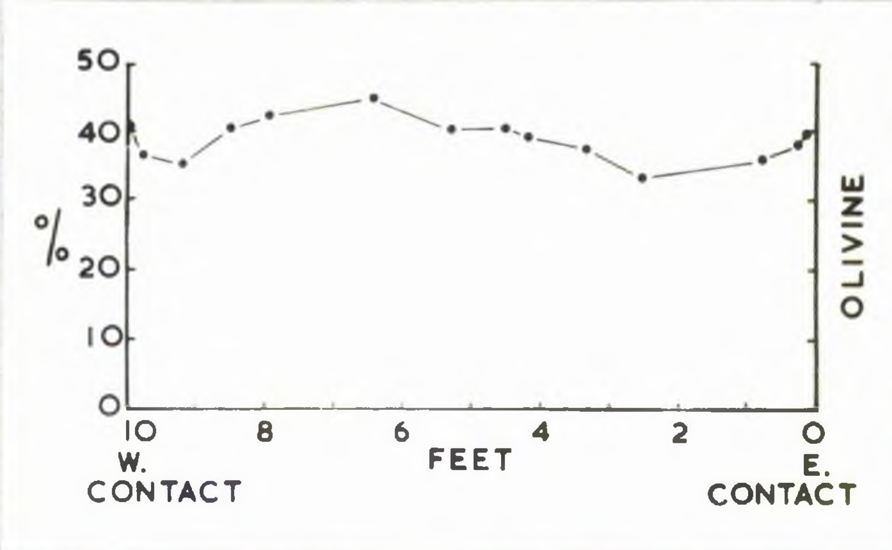

Fig. 63. Distribution of olivine across dyke 31 in outcrop 31/2.

g) Types of Olivine Distribution.

The olivine distribution curves recorded above may be regarded as being of five principal types. An ideal example of each type is illustrated in Fig. 64.

Type (i) (Fig. 64a) has a single maximum at or near the centre of the dyke and the olivine content decreases towards the edges of the dyke with the gradient of the distribution curve greatest near the margins. Dyke 29 exhibits an olivine distribution of this type.

Type (ii) (Fig. 64b) is basically similar to type (i) but the curve is relatively flat in the central part of the dyke. The curve for dyke 9 (outcrop 9/4) is

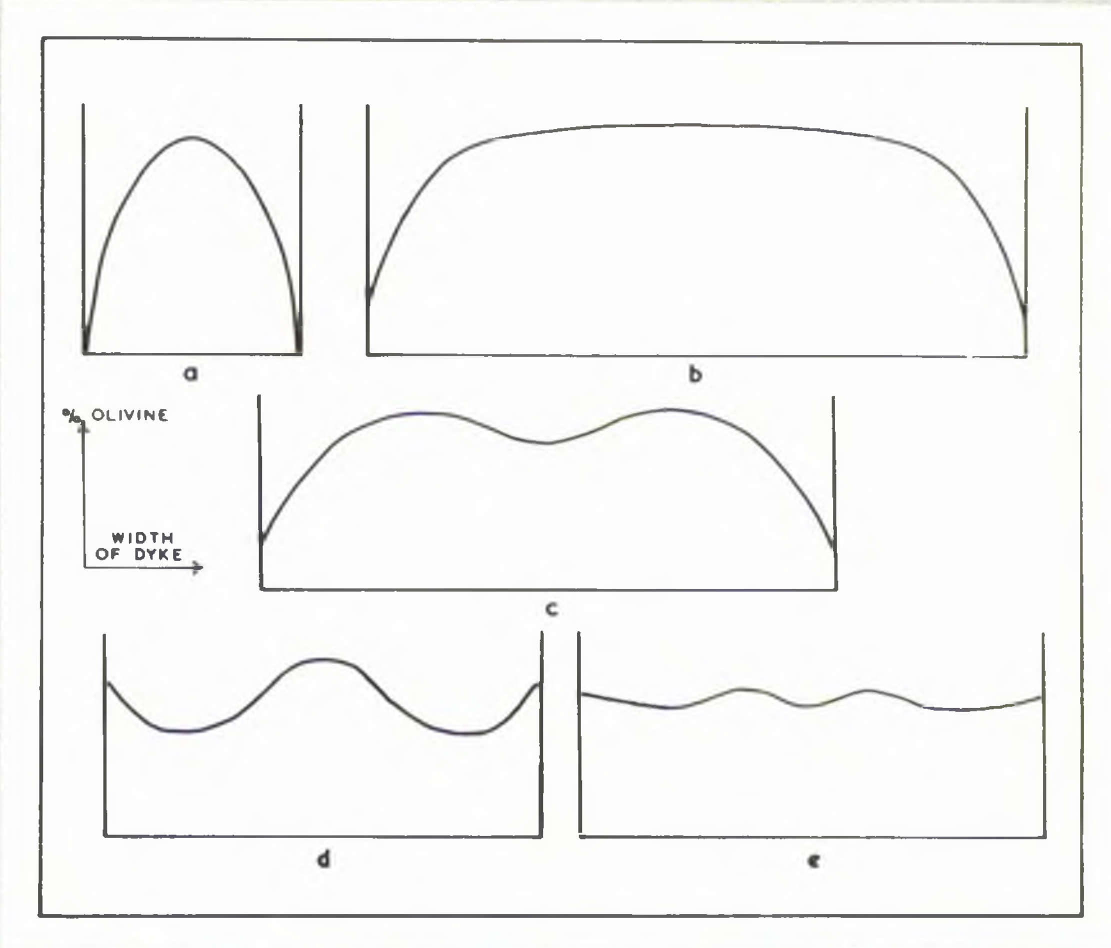

Fig. 64. Principal types of olivine distribution curve.

part of a curve of this type.

Type (iii) (Fig. 64c) is a slight modification of type (ii). Instead of the curve being relatively flat in the centre of the dyke it is bimodal with a small decrease in the olivine content at, or near, the axis of the dyke. The curve for dyke 1 (outcrop 1/10) is slightly bimodal and is therefore of this type, although it could be regarded as transitional between the second and third types. The olivine distribution curve for dyke 1 (outcrop

1/2) appears to be of type (ii), but it would probably be similar to that for outcrop 1/10 if it was complete.

Type (iv) (Fig. 64d) has a single central maximum from which the olivine content decreases towards the contacts but increases again before reaching them. The distribution of olivine across dyke 31 is of this nature.

Type (v) (Fig. 64e) is related to type (iv) in the same way as the third type is to the second: the single central maximum is replaced by two maxima. In this type variation in olivine content across the dyke is comparatively small. The curve for dyke 2 is part of a curve of this type.

The examples presented in Fig. 64 are all ideal cases and in practice the curves depart slightly from these. The principal difference is that the curves are rarely symmetrical. The two halves of the curve are often slightly different and are seldom equally distributed about the axis of the dyke. The significance of these distribution curves is discussed below (chapters X and XI).

VII. MINERAL COMPOSITIONS.

1. DETERMINATIVE METHODS.

The compositions of the olivine, pyroxene and plagioclase in the centres and margins of several of the dykes have been determined optically. The normal methods were employed for the respective minerals and these need only be outlined here. It is, however, necessary to define the limits of accuracy of the various methods and these limits are given below.

The composition of olivine was determined independently from the optic axial angles and from the value of n_β. The optic axial angles across both the acute and obtuse bisectrices were measured directly on the universal stage using only double axis measurements. Orthoscopic and conoscopic methods were used under the conditions favouring maximum accuracy (Munro, 1963 p. 321), and the correspondence between results obtained by both methods was excellent. In every case there was a discrepancy between the mean optic axial angles measured over the acute and obtuse bisectrices (cf. Wyllie, 1959, p. 49-57). This discrepancy ranged between 2.0° and 3.8°. The average of $2V_\alpha$ and $180-2V_\gamma$ (Munro, 1966, p. 765) was used to determine the composition from the table given by Tomkeieff (1939, table 1) and modified by Johnston (1953, p. 166). This table was used in preference to the linear graphs given by Deer and Wager (1939, fig. 1). Deer, Howie and Zussman (1962, i, fig. 11) and others, for the reasons outlined by Johnston (1953, p. 167). The error in the average optic axial angle is probably less than 1° but this is equivalent to an error of 3% Fa. The value of n_β was determined by the oil immersion method using suitably orientated grains picked from thin sections. The corresponding composition was obtained from the graphs given by Bowen and Schairer (1935, fig. 25). The error is probably less than 0.002 and, since this is equivalent to an error of only 1% Fa, this method is obviously the more accurate of the two. However, differences between the compositions obtained from the average optic axial angle and n_β are small (see below) and the average of the two results is taken as the composition.

The composition of clinopyroxene in terms of $CaSiO_3$:$MgSiO_3$:$FeSiO_3$ was obtained from the values of $2V_\gamma$ and n_β using the curves given by Muir (1951, fig. 4). The optic axial angle and the refractive index were determined in the same way as those of olivine. Although the error in individual measurements of $2V_\gamma$ is probably less than $\frac{1}{2}^\circ$, small variations in the optic axial angle occur between crystals and even within single crystals (cf. Brown, 1957, p. 535). This does not appear to be due to zoning and the composition was obtained from the mean of all the determined values for a single specimen.

The anorthite content of the unzoned cores of plagioclase crystals was determined from the data given by van der Kaaden (1951, columns 1A and 2A) and Slemmons (1962, plates 1-10). Slight discrepancies exist between the compositions given by the two sets of data but, in the compositional range concerned (see below), these are within the limits of experimental error and the mean of the two results, rounded to the nearest 1% An, is taken as the composition. The error is probably less than $1\frac{1}{2}$% An.

Attempts have also been made to determine the extent of the marginal zoning of plagioclase crystals by measuring the maximum extinction angle of the outermost zones of some of the more highly zoned examples, but these results are of little significance (see section 3-below).

2. OLIVINE

The optic axial angles, refractive indices and corresponding compositions of the olivine in the centres and margins of some of the dykes are presented in Table 16. The variation in the optic axial angle is within the limits of accuracy of the determinative method.

TABLE 16

Olivine compositions.

DYKE	PART	$2V_\alpha$	$2V_\gamma$	$\frac{2V_\alpha + 180-2V_\gamma}{2}$	=% Fa	n_β	=% Fa	COMPOSITION
1	Centre	89.4°	87.3°	91.1°	11	1.672	10	$Fa_{10.5}$
	Margin	90.7°	87.3°	91.7°	9.5	1.672	10	$Fa_{9.8}$
6	Centre	89.1°	87.3°	90.9°	11.5	1.672	10	$Fa_{10.8}$
9	Centre	89.2°	87.3°	91.0°	11.5	1.672	11	$Fa_{11.3}$
	Margin	89.0°	87.2°	90.9°	11.5	1.673	10.5	$Fa_{11.0}$
31	Centre	89.2°	87.3°	91.0°	11.5	1.678	13	$Fa_{12.3}$

Apart from that for dyke 31, which is noticeably higher, the values of n_β are also constant within the limits of accuracy. It therefore appears that (with the possible exception of dyke 31 in which it may be slightly more fayalitic) the composition of the olivine is constant (Fa_{11}) throughout the dykes.

From the proximity of individual determinations to the mean results it seems that the crystals in a single specimen are all of the same composition. However, optical methods would be unlikely to detect very small compositional variations between crystals, and a statistical survey using an electron probe microanalyser would be necessary to determine whether or not the crystals exhibit a small range of compositions. The optically determined compositions of the olivine in dykes 1 and 9 are very similar to the normative compositions (Table 24).

Olivines of similar compositions have been recorded from other ultrabasic intrusions in Skye, Soay and Rhum. The cumulus olivine in the layered sequence of south-west Rhum varies from $Fa_{11\frac{1}{2}}$ to Fa_{18} (Wadsworth, 1961, p. 29) and is, therefore, generally more iron-rich than that in the dykes. Drever and Johnston (1958, p. 480) determined the compositions of the olivine in several of the picritic minor intrusions in their Hebridean group and found them to range from Fa_7 to Fa_{14}. Perhaps the most significant comparison of the olivine in the dykes is with that of the Sgurr Dubh ultrabasic intrusion. Weedon (1965, p. 57-51) found $2V_\alpha$ of the olivine in the Sgurr Dubh rocks to be 91°, except in the highest zone where it decreased to 89°. Although Weedon equated the $2V_\alpha$ of 91° with a composition of Fa_{13}, he obtained this result by using the graph given by Deer, Howie and Zussman and it is therefore evident that the olivine in the dykes is virtually identical in composition with that in all but the highest rocks of the Sgurr Dubh intrusion. It may also be significant that the dykes geographically nearest to the highest part of the Sgurr

Dubh intrusion are dykes 30 and 31 and that the olivine in the latter may be slightly more fayalitic than in the other dykes. However, in view of the limits of accuracy of the determinative methods, the actual compositional variations are too small to provide definite evidence of such a relationship.

3. CLINOPYROXENE.

The refractive indices, optic axial angles and compositions of pyroxene from the centres and margins of dykes 1 and 9 and the centre of dyke 31 are presented in Table 17. The variations in the optic axial

TABLE 17

Clinopyroxene compositions

DYKE	PART	$2V_\gamma$	n_β	COMPOSITION Ca:	Mg:	Fe:
1	Centre	51.6°	1.684	42:	47:	11
	Margin	52.1°	1.685	43:	46:	11
9	Centre	52.3°	1.685	43:	46:	11
	Margin	51.2°	1.684	42:	47:	11
31	Centre	51.5°	1.686	42:	45:	13

angle and the refractive index are within the limits of accuracy of the determinative methods and thus the composition of the clinopyroxene may be regarded as constant throughout the dykes. The correspondence between the optically determined and normative (Table 24) compositions of the pyroxene in dykes 1 and 9 is poor.

For the clinopyroxenes of the picritic minor intrusions Drever and Johnston (1958, p. 484-485) recorded values of $2H_{\gamma}$ in the range 52^{o} to $57\frac{1}{2}^{o}$ [$2H_{\gamma}$ for the pyroxene in the dykes is 56.8^{o}]. Although Drever and Johnston did not determine the compositions of these pyroxenes there is little doubt that they are similar to those in the dykes. Weedon (1965), unfortunately, does not give any optically determined compositions of the clinopyroxenes in the Sgurr Dubh ultrabasic rocks, but the writer has determined $2V_{\gamma}$ and n_{β} of the clinopyroxene in a single specimen from the upper part of this intrusion in Coir' a' Ghrunnda. The values obtained are $52\frac{1}{2}^{o}$ and 1.683 respectively. This indicates that the pyroxene in the Sgurr Dubh layered ultrabasic rocks is virtually identical with that in the dykes.

4. PLAGIOCLASE.

The compositions of the unzoned cores of the plagioclase crystals in the centres of dykes 1, 9 and 31, and in the margins of dykes 1, 2 and 9 are presented in Table 18. It appears that throughout the dykes the cores of the plagioclase crystals have a composition of An_{84} ($\pm$ $1\frac{1}{2}$% An). Also given in Table 18 are the maximum extinction angles in the zone perpendicular to (010) of the outermost zones of some of the more extensively zoned crystals and their corresponding compositions [determined from the graph given by van der Kaaden (1951, fig. 12)]. The amount of zoning varies considerably from one crystal to another and the results presented in Table 18 are for the most highly zoned crystal

TABLE 18.

Plagioclase compositions

DYKE	PART	COMPOSITION OF CORES	OUTERMOST ZONES Maximum extinction angle in the zone perpendicular to (010)	Composition
1	Centre	An_{83}	30^{o}	An_{55}
	Margin	An_{84}	28^{o}	An_{53}
2	Margin	An_{85}	32^{o}	An_{59}
9	Centre	An_{84}	12^{o}	An_{30}
	Margin	An_{84}	20^{o}	An_{38}
31	Centre	An_{85}	26^{o}	An_{48}

observed in several thin sections of each rock. Since extensively zoned crystals are relatively rare in most of these rocks and the method is therefore comparatively inaccurate, the compositions of the outermost zones given in Table 18 can only be regarded as first approximations to the true extent of the marginal zoning. The structural state of the unzoned cores of the plagioclase crystals was also determined from the data given by van der Kaaden and Slemmons. They were found to fall practically on the low temperature (van der Kaaden) or plutonic (Slemmons) curves. Since the unzoned cores generally make up more than 95% of the individual crystals their compositions are very close to the average compositions of the crystals and this is reflected by the relationship between the optically determined compositions of the cores and the normative compositions (Table 24) for the plagioclase in dykes 1 and 9.

Plagioclase of similar composition occurs in the ultrabasic rocks of Rhum. Wadsworth (1961, p. 29), recorded compositions ranging from An_{85} to An_{78} with some of the crystals marginally zoned to compositions more sodic than An_{60} (p. 49). Drever and Johnston (1958, p. 485) gave the compositions of marginally zoned plagioclase crystals in the Kinloch sill and Sill 2 in Soay as An_{85-40} and An_{83-42} respectively. The composition of the plagioclase in most of the layered ultrabasic rocks of Sgurr Dubh is An_{85} (Weedon, 1965, p. 47-51), but in some of the highest rocks of the series it is An_{80}. Weedon (1965, p. 50), has also recorded plagioclase crystals with cores of An_{88} marginally zoned to An_{74} in some of the felspar-rich bands. Marginal zoning, however, is generally slight or absent in the Sgurr Dubh rocks.

It seems, therefore, that the calcic bytownite occurring in the dykes is relatively common in Tertiary non-alkaline ultrabasic rocks in the Hebridean area.

VIII. VARIATIONS IN CRYSTAL SIZE.

1. METHODS OF CRYSTAL MEASUREMENT.

a) Olivine.

A simple, rapid method was devised for determining the size of olivine crystals. A normal thin section was mounted in front of a piece of polaroid in a 2" x 2" photographic slide projector and the resulting image was focussed on a screen at a magnification of X 50. The screen used was white paper ruled into 2 cm squares to eliminate the possibility of the same crystal being counted twice. A second piece of polaroid, mounted in a clamp-stand, was placed in the light beam and could be withdrawn when necessary, thus serving as an analyser. The magnified images of the olivine crystals were measured with a transparent plastic ruler.

b) Plagioclase.

Unfortunately, the plagioclase crystals, unlike the olivines, do not always occur as easily identifiable, discrete individuals and rotation between crossed nicols is often required to locate the boundaries of the crystals. This precludes the use of the rapid method outlined above since this method does not permit rotation of the thin section relative to the plane of polarization. The method employed by Pye (1965, p. 10-11), is unsatisfactory for the plagioclase in the dykes due to the comparatively large size of many of the crystals. A modification of the method used for olivine crystals was adopted. A thin section was mounted on a mechanical stage attached to a microprojector and the magnified images of the plagioclase crystals were measured as before. The main disadvantages of this method, compared with that used for olivine crystals, are that:- (i) it is very much slower; (ii) only a small circular field is visible at one time and (iii) individual crystals frequently transgress the perimeter of the field and therefore cannot be measured.

2. OLIVINE.

a) Range of Sizes.

The olivine crystals in the dykes range from minute grains barely identifiable under the microscope to phenocrysts more than a centimetre long. In many ultrabasic dykes and sills (Drever and Johnston, 1958, p. 480), two "generations" of olivine crystals have been distinguished. These "generations" consist of phenocrysts and small "groundmass" olivines. Although very large crystals do co-exist with minute grains in the dykes, there appears to be a continuous gradation in size rather than two "generations". The possibility of the existence of two size groups of olivine crystals in the dykes has been investigated by measuring the lengths of over 1,000 crystals in a representative sample. The size/frequency diagram based on these results (Fig. 65) has a single maximum. If two "generations" of crystals were present the graph would be bimodal with a major maximum representing the average length of the "groundmass" olivine crystals and a minor one representing the average length of the phenocrysts. This confirms the existence of a single

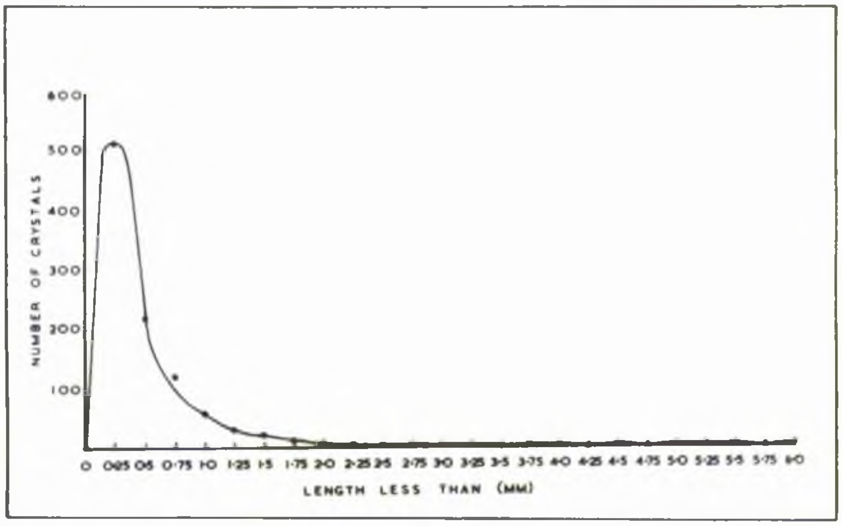

Fig. 65. Length/frequency diagram for olivine crystals in a specimen from the centre of dyke 1.

"generation" of olivine crystals in the dykes (cf. Wyllie and Drever, 1963, p. 162-167).

The average size of the olivine crystals varies across the dykes. In order to study these variations the average lengths of the olivine crystals in specimens collected across the dykes have been determined. At least 300 crystals were measured in each specimen. Crystals less than 0.1 mm long were omitted from the averages since very small crystals cannot be measured accurately and the large numbers of these crystals present would tend to obscure the variations.

This omission does not invalidate direct comparison of the results as the proportion of crystals less than 0.1 mm long is relatively constant.

The results for three of the dykes are presented below in the form of transverse crystal size profiles. These correspond to three of the distribution diagrams given in chapter VI.2.

b) Dyke 1.

Outcrop 1/10 was selected for crystal size analyses in preference to outcrop 1/2 as it presents a more complete cross-section of the dyke, the latter being cut longitudinally by a basic dyke. The average lengths of the olivine crystals in 14 specimens from dyke 1 are given in Table 19 and the variation across the dyke is illustrated in Fig. 66.

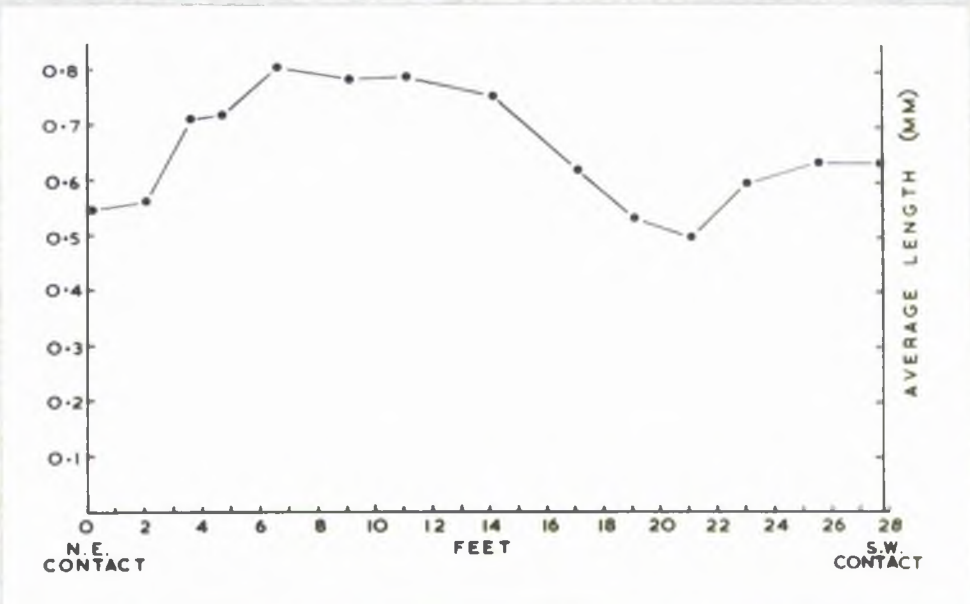

Fig. 66. Transverse variation in the average length of the olivine crystals in dyke 1 (outcrop 1/10)

TABLE 19

Average length of the olivine crystals in specimens from dyke 1 (outcrop 1/10)

Distance from N.E. contact Ft.	Ins.	Average length of olivine crystals (mm).	Distance from N.E. contact Ft.	Ins.	Average length of olivine crystals. (mm).
0	2	0.549	14	1	0.757
2	1	0.562	17	1	0.624
3	7	0.713	19	1	0.536
4	8	0.719	21	1	0.501
6	7	0.807	23	1	0.600
9	1	0.787	25	7	0.638
11	1	0.794	27	9	0.635

In the north-east half of the dyke the average length of the olivine crystals varies sympathetically with the olivine content (cf. Figs. 66 and 57) but in the south-west half the relationship is antipathetic. In addition, the average length of the olivine crystals at the south-west contact is slightly greater than that at the north-east contact. This asymmetrical variation in the size of the olivine crystals is discussed in chapter XI.3.

c) Dyke 6.

The average lengths of the olivine crystals in 9 specimens from dyke 6 (outcrop 6/6) have been determined. These are presented in Table 20 and are plotted against the position of the specimen in the dyke in Fig. 67. The average length of the olivine crystals is the same at both contacts and increases away from the edges of the dyke. The transverse size profile

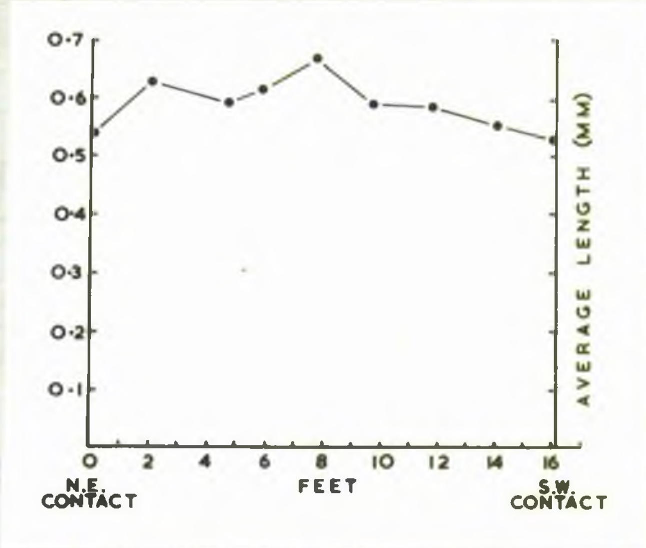

Fig. 67. Transverse variation in the average length of the olivine crystals in dyke 6 (outcrop 6/6).

TABLE 20.

Average lengths of the olivine crystals in specimens from dyke 6 (outcrop 6/6)

Distance from the N.E. contact Ft.	Ins.	Average length of olivine crystals (mm).
0	0½	0.539
2	1	0.627
4	9	0.594
5	11	0.615
7	10	0.667
9	9	0.591
11	10	0.586
14	1	0.551
16	1	0.530

(Fig. 67) is bimodal and asymmetrical about the axis of the dyke. Comparison of Fig. 67 with Fig. 59 indicates that the average length of the olivine crystals is directly proportional to the olivine content. The total variation in the average length of the olivine crystals is less than 0.15 mm, compared with more than 0.3 mm in dyke 1.

d). Dyke 31.

The average lengths of the olivine crystals in 9 specimens from dyke 31 (outcrop 31/2) are given in Table 21. Fig. 68 is the corresponding transverse crystal size profile.

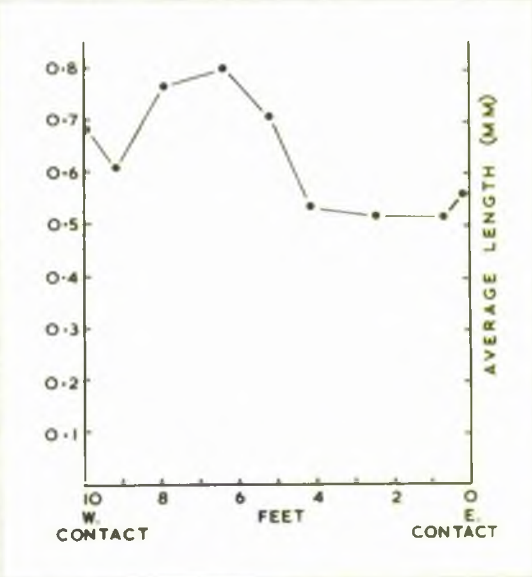

Fig. 68. Transverse variation in the average length of the olivine crystals in dyke 31 (outcrop 31/2).

Like the olivine distribution curve (Fig. 63), the crystal size profile is slightly asymmetrical. The average length of the crystals varies sympathetically with the olivine content and the two curves (Figs. 63 and 68) have the same general form. The only notable difference

TABLE 21

Average lengths of the olivine crystals in specimens from dyke 31 (outcrop 31/2)

Distance from E. contact. Ft.	Ins.	Average length of olivine crystals (mm).
0	3	0.561
0	9	0.517
2	6	0.519
4	2	0.536
5	3	0.707
6	5	0.802
7	11	0.766
9	2	0.608
9	11½	0.681

between the two is that the average lengths of the olivine crystals at the two contacts differ by more than 0.1 mm whereas the olivine contents are the same at both contacts. The significance of this is discussed below (chapter XI.3).

3. PLAGIOCLASE.

a) Range of Sizes.

Although the plagioclase crystals vary considerably in size, the crystals in a single specimen usually fall within a relatively limited range of sizes (chapter V.2.d). Occasionally, however, a dyke or part of a dyke, in which most of the felspar crystals are relatively small, contains a few much larger examples which appear to be phenocrysts, e.g. the margins of dyke 2. The lengths of approximately 2,000 plagioclase crystals in a specimen from near the south-west margin of dyke 2 have been determined. A length/frequency diagram for the measured crystals (Fig. 69) indicates that there is a continuous range of sizes and thus only a single "generation" of plagioclase crystals is present in the rock. The larger crystals are therefore pseudo-phenocrysts. Less than 7% of the felspar crystals are more than 0.5 mm long.

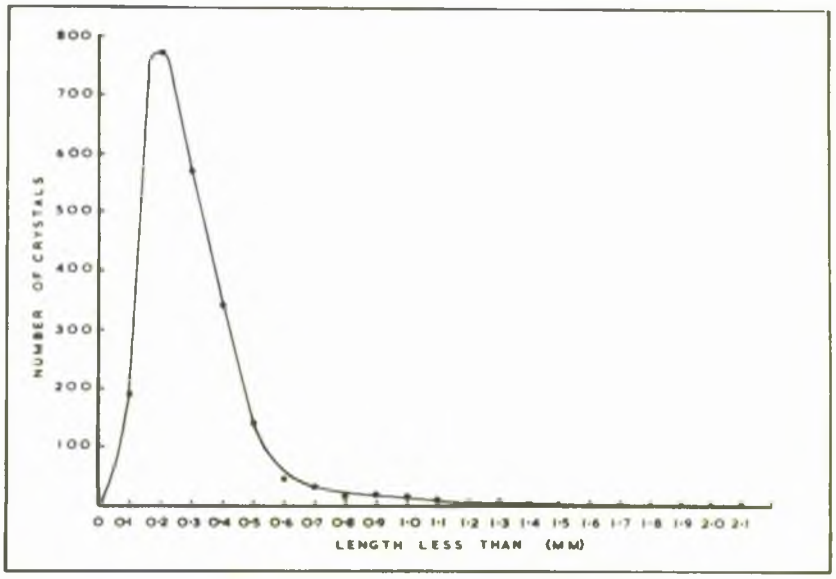

Fig. 69. Length/frequency diagram for the plagioclase crystals in a specimen from the south-west margin of dyke 2.

b) Dyke 1.

The plagioclase crystals do not vary noticeably in size across some of the dykes but in others they become much smaller towards the contacts. Dyke 1 is of the latter type and the size variation across this dyke has been studied quantitatively. The average lengths and breadths of the plagioclase crystals in specimens from dyke 1 (outcrop 1/10) are given in Table 22 and are plotted against the position of the specimen in the dyke in Fig. 70.

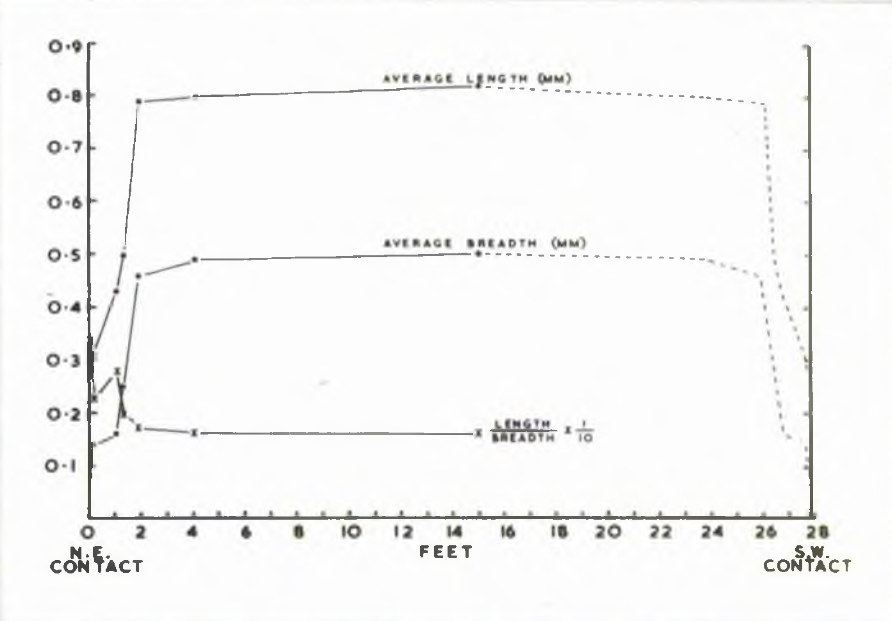

Fig. 70. Transverse variations in the length, breadth and length:breadth ratio of plagioclase crystals in dyke 1.

TABLE 22

Size analyses of the plagioclase crystals in specimens from dyke 1 (outcrop 1/10)

Distance from N.E. contact Ft.	Ins.	Average length (mm).	Average breadth (mm).	Length / breadth
0	0½	0.267	0.079	3.38
0	2	0.308	0.137	2.25
1	1	0.433	0.156	2.78
1	4	0.499	0.253	1.97
1	11½	0.790	0.457	1.73
4	1	0.804	0.489	1.64
15	1	0.818	0.503	1.63

The dimensions of the plagioclase crystals have only been determined for specimens from one half of the dyke but visual comparison with corresponding specimens from the other half indicates that the variation in the size of the plagioclase crystals is essentially symmetrical about the centre of the dyke. Consequently, the curves in Fig. 70 can be extrapolated (dashed lines) to the other half of the dyke. Visual examination also shows that there is little or no change in the size of the crystals in the gap between the analysed specimens from 4 ft. 1 in. and 15 ft. 1 in.

It is beyond doubt that the pyroxene and most of the plagioclase crystallized after the emplacement of the dykes (see chapter XL.2). In a dyke such as dyke 1, therefore, the size of the plagioclase crystals is governed by the conditions under which the dyke cooled. Variations in the size of plagioclase crystals from the margins to the centres of dykes have been studied by Winkler (1948) and his results indicate that, although the form of the transverse crystal size profile varies with the width of the dyke, variations of the type shown in Fig. 70 are produced under normal cooling conditions for a dyke, i.e. when the loss of heat is outwards through the dyke walls. Although the variations in the size of the plagioclase crystals are not identical in all the dykes the differences can be attributed to slightly differing cooling conditions. In this respect the transverse variations in the size of the plagioclase crystals differ markedly from those in the size of the olivine crystals which cannot be attributed to the cooling of the dyke (see chapter XI).

IX. INTER-DYKE VARIATION IN OLIVINE CONTENT

1. OLIVINE CONTENTS.

In addition to the variations in olivine content across individual dykes, corresponding parts of different dykes contain different amounts of olivine. This is best illustrated by the variation in the olivine contents of the centres of the dykes. The olivine contents of the centres of seventeen of the dykes have been determined, sometimes at more than one locality, and these are presented in Table 23.

TABLE 23

Olivine contents of the centres
of the dykes in 20 outcrops

DYKE	OUTCROP	OLIVINE CONTENT OF CENTRE
1	(1/2)	66.5%
1	(1/10)	65.0%
2	(2/1)	48.0%*
3	(3/4)	73.5%*
6	(6/6)	60.7%
6	(6/7)	61.0%
8	(8/1)	49.3%
9	(9/4)	67.8%*
10	(10/1)	71.7%
13	(13/2)	53.9%
15	(15/2)	53.1%
16	(16/1)	19.0%
18	(18/3)	48.8%
20	(20/2)	53.7%
21	(21/1)	59.6%
27	(27/3)	61.2%
29	(29/1)	35.6%
29	(29/2)	39.8%
31	(31/2)	40.2%
33	(33/1)	66.5%

* Since the exact widths of the dykes in outcrops 2/1, 3/4 and 9/4 are not known the values given may not be for the true centre of the dyke.

The overall variation in the olivine contents of the centres of the dykes is more than 50% and consequently, it cannot be attributed entirely to the differences in the type of olivine distribution in individual dykes. It can only be concluded, therefore, that the dykes differ in their average olivine contents and that the olivine content of the centre of each dyke is related to its average olivine content. Attempts are made below to determine the factors controlling the olivine contents of the dykes.

2. RELATIONSHIP TO OTHER FACTORS.

a) Location.

Harker (1904, p. 375) observed that the dykes "have a radiate disposition about a centre" in the heart of the Cuillins and Bowen (1928, p. 150) stated that "there is a very distinct tendency for the more extreme types to occur only close in towards the centre and for those dykes which are found far out to show only moderate enrichment in olivine". The relationship between the olivine contents of the centres of the dykes and the locations of the sampled outcrops has been systematically investigated and the results of this investigation are presented below.

If the dykes are extrapolated towards the centre of the Cuillins most of them pass through or close to a "centre" low in Coir' an Lochain. There are, however, several dykes which do not pass particularly close to this "centre", the most notable of these being the dykes on the west spur of Sgurr Dearg, i.e. 27, 28 and 29. The apparent radiation of all the dykes except dyke 10 from the arcuate ultrabasic intrusion of Sgurr

Dubh is considered to be more significant than their relationship to a hypothetical "centre" (see chapter XVI. 2). Consequently, the olivine contents of the centres of the dykes have been plotted against the distances of the sampled outcrops from the convex margin of this intrusion (Fig. 71) rather than from the "centre". In actual practice, plotting the olivine contents against both distances would produce similar results, since the hypothetical "centre" lies close to the Sgurr Dubh intrusion on its concave side.

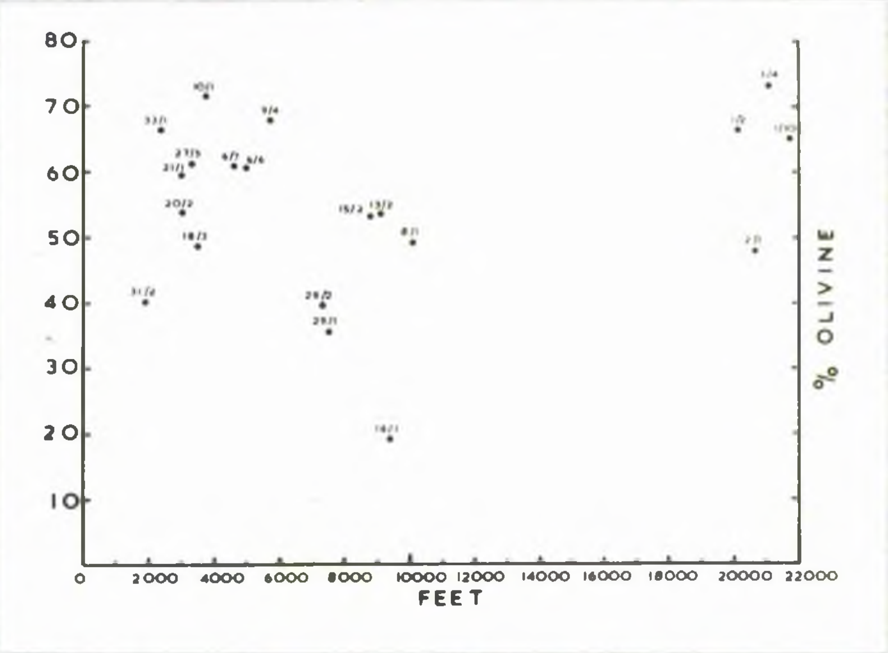

Fig. 71. Olivine contents of the dyke centres plotted against the distance of the sampled outcrops from the Sgurr Dubh ultrabasic intrusion.

The olivine content of the centre of the longest dyke (dyke 6) increases slightly towards the centre of the Cuillins (chapter V.2.i) in accordance with Bowen's statement. The dykes furthest from the

Sugrr Dubh intrusion are those on Ben Cleat, i.e. 1, 2 and 3. Since the central parts of dykes 1 and 3, which contain more than 65% olivine, are among the most olivine-rich, it appears that the relationship suggested by Bowen does not exist. This is confirmed by the random distribution of the points in Fig. 71. There is, therefore, no simple relationship between the locations of the dykes and their olivine contents.

b) Altitude.

Bowen (1928, p. 151), observed that one of the dykes on Sgurr nan Gobhar [either dyke 14 or dyke 15] became poorer in olivine as it was traced upwards. Since this suggests that there may be a relationship between the olivine content of a dyke and its altitude, the olivine contents of the centres of the dykes have been plotted against the approximate altitudes of the sampled outcrops (Fig. 72). The points in Fig. 72 are randomly distributed and it must therefore be concluded that there is no simple relationship between the altitude of an outcrop and the olivine content of the dyke.

Bowen's observations also suggest that there may be a relationship between olivine content and altitude within individual dykes and this possibility has also been examined. Dyke 14, which is probably the one described by Bowen, shows a slight decrease in olivine content towards its higher outcrops.

In the case of dyke 1, outcrop 1/10 is approximately 100 feet higher than outcrop 1/2 but the upwards decrease in olivine content

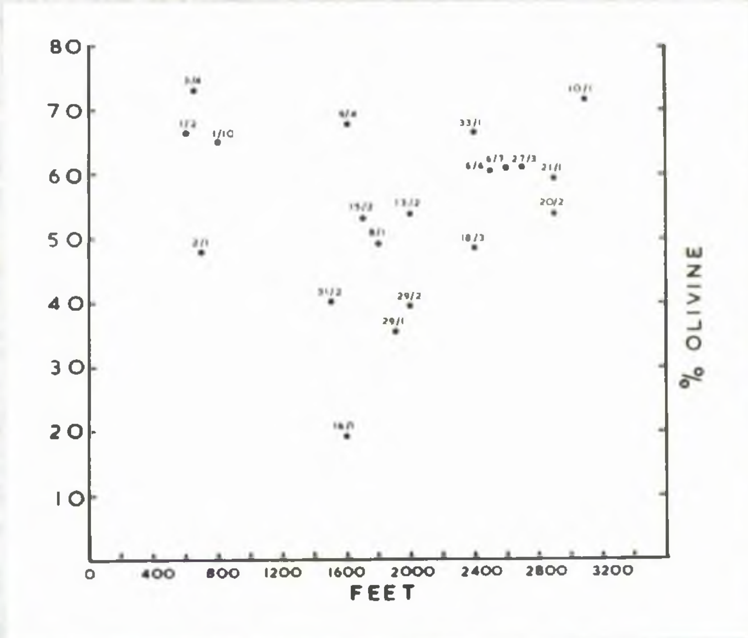

Fig. 72. Olivine contents of the dyke centres plotted against the altitudes of the sampled outcrops.

is only 1½%, which is close to the limits of determinative error. Outcrop 6/7 is more than 150 feet above outcrop 6/6 but the dyke centre contains practically the same amount of olivine in both outcrops and in dyke 29, the olivine content actually increases upwards by more than 4% in 100 feet. It appears, therefore, that the variations in olivine content with elevation in individual dykes are small and unrelated to the altitude.

c) Width of the Dyke.

Bowen established that the larger dykes contained more olivine than the smaller ones but, as the small dykes on which he based this conclusion were undoubtedly of the Coire Lagan type and not the Ben Cleat type, the existence of such a relationship within the Ben Cleat type remains to be proved.

Narrower dykes such as 29 and 16 generally contain less olivine than wider ones such as 1 and 9, thus implying the existence of a relationship of the type suggested by Bowen. In Fig. 73 the olivine contents of the dyke centres have been plotted against the widths of the sampled outcrops. Since the sampled outcrops (with the exception of those mentioned below) were selected because the widths of the dykes in these outcrops are approximately equal to the average widths of the dykes, the points (solid circles) in Fig. 73 are effectively plots of the olivine content against the average width of the dyke. It can be seen from Fig. 73 that there is a definite tendency for low olivine contents to be confined to narrow dykes. The dashed line in Fig. 73 represents the approximate trend of the relationship.

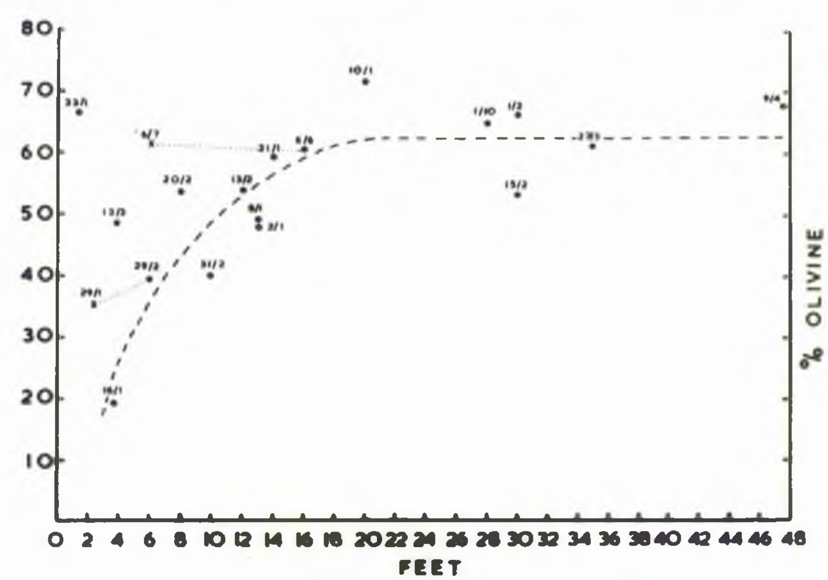

Fig. 73. Olivine contents of the dyke centres plotted against the widths of the dykes in the sampled outcrops.

The points plotted in Fig. 73 do not lie exactly on the trend curve but are scattered about it. There are three main reasons for this scattering. Firstly, it is evident from the olivine distribution curves (Figs. 56-63) that for some types of distribution the olivine content varies by as much as 10% within the central part of the dyke and, since the distribution curves are seldom perfectly symmetrical about the centre of the dyke this variation will cause scattering. Secondly, some of the types of distribution curve do not have maxima at or near the centre of the dyke, and lastly, the dykes are subject to local variations in width and it is sometimes difficult to obtain the true average width of a dyke. In addition, in some of the outcrops, e.g. 2/1 and 9/4, the dykes are only partially exposed and their widths can only be estimated. [These are plotted as open circles in Fig. 73.] In outcrop 3/4 dyke 3 is more than 17 feet wide but it is not possible to estimate the true width of the dyke either from its field relations (cf. dyke 2) or from its distribution curves (cf. dyke 9) and consequently, it has been omitted from Fig. 73. Inaccuracies in the widths of the dykes will cause most scattering where the trend curve is steep and it is noticeable that the deviation of the points from the trend curve is greatest in this region.

Where a dyke is much narrower than the average width of the dyke (e.g. in outcrop 6/7 dyke 6 is only 6 feet wide whereas in all the other outcrops dyke 6 is more than 15 feet wide) there is virtually no difference in the olivine content. The olivine contents of the dyke centres in two such outcrops (crosses in Fig. 73) have been plotted to illustrate this. It therefore appears that the olivine content of a dyke is not seriously affected by local variations in width.

The plot of the specimen from the centre of dyke 33 lies very far from the trend curve and this anomaly cannot be attributed to any of the above causes. This dyke is never more than 2 feet wide and contains over 60% olivine. It is noteworthy that dyke 33 also has a slightly different contact relationship from the other dykes (chapter V.2.j) and an exceptionally coarse grain-size (Table 7) for such a narrow dyke. It is possible that it is not of the Ben Cleat type, but, if it is to be included in the Ben Cleat group, it must be regarded as an anomalous small dyke which exhibits many of the properties of a dyke more than ten times its width.

It therefore appears, despite the exception, that the width of a dyke exerted some control on its olivine content. This control was unaffected by local changes in width and consequently must have been of a very fundamental nature. The significance of this is discussed below (chapter XI. 3).

X. DIFFERENTIATION.

A cursory glance at the mineral distribution curves is sufficient to indicate that the dykes are differentiated. Four specimens of dyke rock, three of which are from different parts of the same dyke, have been chemically analysed and the results are given in Table 24.

The analyses of the three rocks from dyke 9 have been plotted (Fig. 74) on an albite/iron ratio diagram (Wager, 1956, p. 219) and compared with the fractionation trend of Hebridean lavas described by Wager (1956, pp. 227-233). It is evident from Fig. 74 that the differentiation

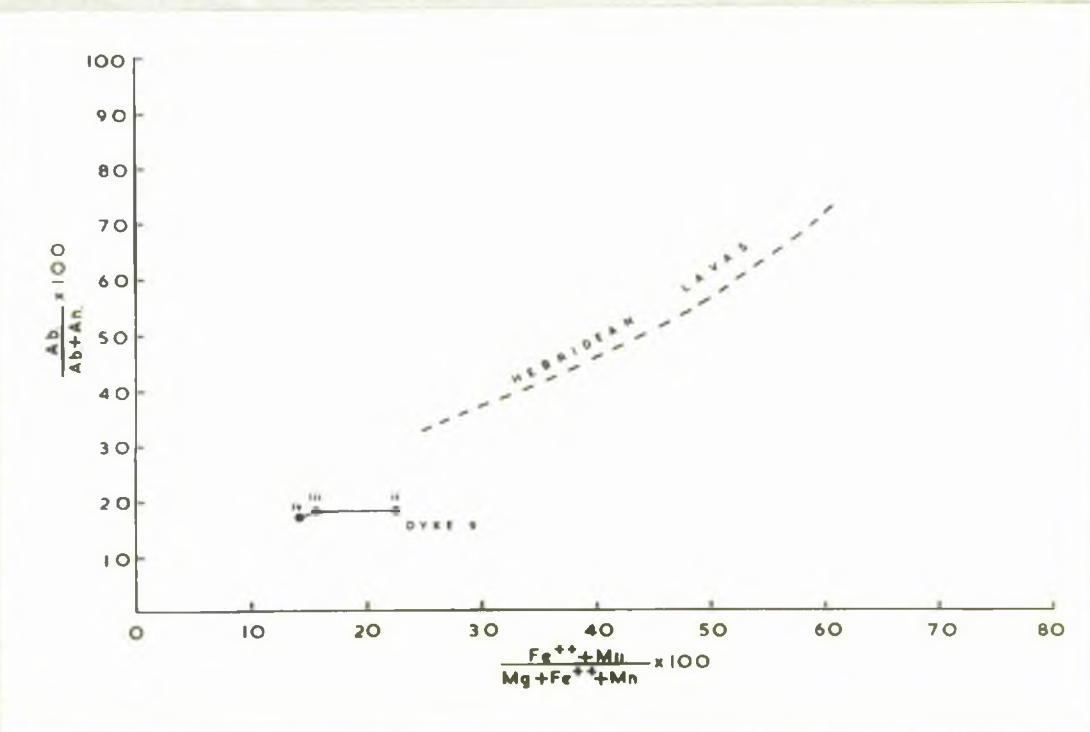

Fig. 74. Albite/iron ratios of Hebridean lavas (after Wager, 1956, fig. 5) and the analysed rocks from dyke 9.

Table 24.

Chemical analyses and norms of specimens from dykes 1 and 9.

No.	Analyses (Wt. %) i	ii	iii	iv
SiO_2	40.29	45.64	42.52	40.11
Al_2O_3	5.41	13.11	8.12	5.93
Fe_2O_3	1.93	3.69	2.41	1.95
FeO	8.16	7.43	8.72	9.54
MgO	35.46	14.58	27.42	32.81
CaO	3.77	10.72	6.27	4.33
Na_2O	0.39	1.39	0.72	0.54
K_2O	0.09	0.13	0.23	0.10
H_2O+	2.21	1.57	1.90	2.39
H_2O-	0.23	0.14	0.17	0.23
TiO_2	0.28	0.78	0.49	0.25
CO_2	0.70	0.59	0.56	0.66
P_2O_5	0.03	0.08	0.04	0.04
Cr_2O_3	0.39	0.14	0.20	0.10
MnO	0.16	0.16	0.18	0.14
	99.50	100.15	99.95	99.12

		Norms (Wt. %) i	ii	iii	iv
Qtz.		-	-	-	-
Or.		0.53	0.77	1.36	0.59
Ab.		3.30	11.76	6.09	4.57
An.		12.75	29.15	18.25	13.46
Wo.)	Di	2.41	9.83	5.27	3.25
En.)	Di	1.88	7.09	3.96	2.45
Fs.)	Di	0.27	1.85	0.78	0.47
En.)	Hy	2.89	10.68	5.88	0.74
Fs.)	Hy	0.42	2.79	1.15	0.14
Fo.)	Ol	58.53	12.99	40.94	55.01
Fa.)	Ol	9.41	3.74	8.84	11.63
Mt.		2.80	5.35	3.49	2.83
Il.		0.53	1.48	0.93	0.47
Crt.		0.60	0.21	0.31	0.15
Ap.		0.07	0.19	0.09	0.09

Mineral compositions (normative)	i	ii	iii	iv
Plagioclase				
An.	86	82	82	83
Ab.	12	17	15	15
Or.	2	1	3	2
Clinopyroxene				
Wo.	50	50	50	50
En.	45	42	43½	43½
Fs.	5	8	6½	6½
Orthopyroxene				
En.	90	83½	87	87½
Fs.	10	16½	13	12½
Olivine				
Fo.	90	83½	87	87½
Fa.	10	16½	13	12½

(i) = Centre of dyke 1.

(ii) = 2" from the N.E. edge of the dyke in outcrop 9/4.

(iii) = 4'4" from the N.E. edge of the dyke in outcrop 9/4.

(iv) = 27'0" from the N.E. edge of the dyke in outcrop 9/4.

Analyst: F.G.F. Gibb.

trend of dyke 9 is markedly different from that of the lavas. In the dyke the albite ratio remains constant and only the iron ratio changes, whereas in the lavas both ratios vary sympathetically. Plotting the analyses on the same type of diagram modified to include ferric iron (Yoder and Tilley, 1962, p. 386-387) gives a similar result. A differentiation trend of the type shown by dyke 9 could arise in two ways. Either the Fe:Mg ratio of the mafic minerals changes without a corresponding change in the composition of the plagioclase or the Fe:Mg ratios of the olivine and pyroxene are different and the relative amounts of these two minerals vary. Since it has already been shown that in dyke 9 the Fe:Mg ratio of the olivine is less than that of the pyroxene (Tables 16 and 17) and that the olivine content increases towards the centre of the dyke (Fig. 61), it seems beyond doubt that the observed differentiation trend in this dyke is due to the second of these alternatives. A similar differentiation trend was obtained for the Kilauea basalts of 1840 (Wager, 1956, p. 221) in which the differentiation mechanism, according to Macdonald (1949, p. 1574), was gravitative accumulation of olivine crystals. It appears, therefore, that a change in the amount of olivine relative to pyroxene is sufficient to produce a differentiation trend of the type shown by dyke 9.

If the analyses of the rocks from dyke 9 are plotted on the type of variation diagram which takes into account the calcium in the clinopyroxene as well as that in the plagioclase (Drever and Johnston, 1966) another feature becomes apparent (Fig. 75). The alkali:lime ratio,

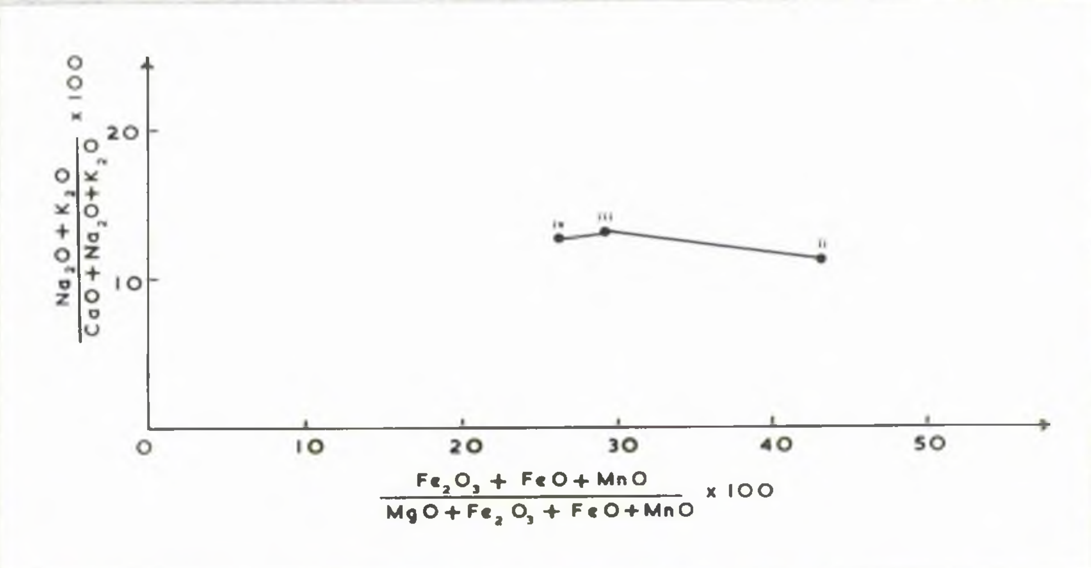

Fig. 75. Variation diagram for dyke 9 (see text).

which is relatively constant throughout the central part of the dyke, decreases slightly near the margins. Since the compositions of the pyroxene and plagioclase are constant throughout the dyke (Tables 17 and 18) this can only be due to a small change in the pyroxene:plagioclase ratio. It can be seen from the distribution curves (Fig. 61) that an increase in this ratio occurs towards the dyke margins.

Since the variations in its petrochemistry can be attributed to variations in the relative amounts of the primary minerals, the differentiation of dyke 9 is best illustrated by plotting the modal analyses, corrected to 100% (see chapter VI. 2.a), as in Fig. 76.

It is noticeable that the pyroxene:plagioclase ratio, which is relatively constant in the central part of the dyke, increases rapidly near the edge of the dyke. [The two points nearest the pyroxene -

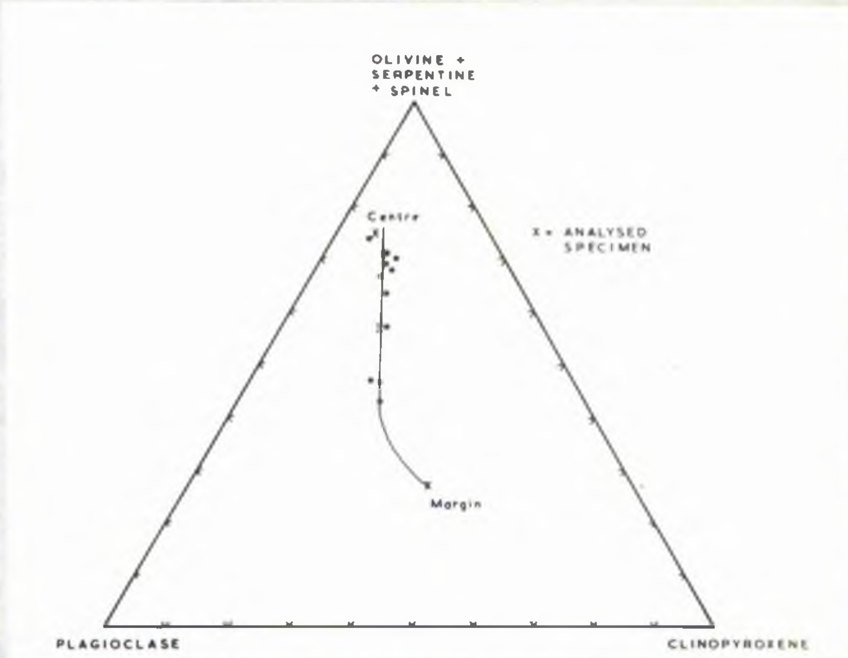

Fig. 76. Modal variation diagram for the N.E. half of dyke 9.

plagioclase side of the triangle are for specimens only one foot apart although the entire line represents a width of 27 feet]. A similar marginal increase in the pyroxene:plagioclase ratio occurs in dyke 2 but is either absent or small in most of the dykes.

The chemical and mineralogical differentiation of the dykes, of which dyke 9 is a representative example, is, therefore, of a type rather different from those commonly described in petrological literature. It is caused by differential movement of olivine, and in some cases a slight differential movement of plagioclase, within the dykes. In the following chapter the processes producing differential migration of crystals are considered in detail.

XI. MECHANISM OF INTRUSION AND DIFFERENTIATION

1. BOWEN'S HYPOTHESIS.

To account for the paucity of olivine in the margins of the dykes relative to their centres Bowen (1928, p. 158) suggested that the dykes were composite intrusions formed as follows:- an olivine-poor, basic magma was intruded: while still hot it acted as a lubricant facilitating the emplacement of an olivine-rich component along the centre of the dyke. He considered that the second magma was in such "an advanced state of crystallization" that intrusion without lubrication was impossible. In the writer's opinion there are a number of serious objections to this hypothesis, quite apart from the exceptional degree of coincidence obviously required to form a whole suite of dykes by this mechanism, and these are considered below.

If a magma as rich in olivine as that proposed by Bowen followed, and "swept out" the central part of a partly crystallized, olivine-poor intrusion, abrupt changes in olivine content should be present at the interfaces of the two magmas. In all the dykes examined by the writer changes in olivine content are gradational. As Bowen's olivine-rich phase contained olivine in the crystalline state, gradational changes in olivine content across the magma interfaces could only have been effected by mechanical mixing of the two magmas. In composite minor intrusions mechanical mixing of the two magmas due to intrusion is generally slight: either the junction between the two is fairly sharp or the earlier member is cut by small veins of the later member (Harker, 1904, p. 258-259; Bailey *et al.*, 1924, p. 223). In minor intrusions as small as the dykes the agents of more extensive mechanical mixing, e.g. convection currents (Wager, *et al.*, 1965, p. 303), would be absent and it therefore appears that, if the dykes were composite intrusions, changes in olivine content of the type recorded in chapter VI.2 would not exist at the junctions between the two members.

It can be seen from the olivine distribution curves that in some of the dykes, e.g. 2 and 31, the margins contain as much olivine as the centres. In such cases, unless complete homogenization of the two magmas occurred after emplacement and prior to further differentiation, the olivine-rich magma must have been intruded without the preceding olivine-poor phase. According to Bowen this was not possible and this evidence is, therefore, incompatible with his theory.

Ultrabasic xenoliths occur in both the centres and margins of the dykes. If, as Bowen proposed, the olivine-poor phase represented the supernatant liquid of a "partially crystallized basaltic magma" and the olivine-rich phase represented the crystal accumulate from the same magma, the cognate xenoliths should be extremely rare in the olivine-poor part of the dyke since they would have been subject to the same accumulation process prior to intrusion as the olivine crystals.

Finally, if the dykes were formed from two magmas which were derived in the manner suggested by Bowen, the minerals which crystallized from the supernatant liquid would not have the same composition as the accumulated crystals or those which crystallised from the intercumulus liquid. However, it has already been established that there are no variations in the compositions of the three main minerals across the dykes and, in addition, the "groundmass" of the dykes is more basic than the basaltic liquid favoured by Bowen.

It is evident therefore that Bowen's hypothesis is inadequate and the remainder of this chapter is devoted to a study of the mechanism of intrusion and differentiation of the Ben Cleat ultrabasic dykes.

2. NATURE OF THE INTRUDED MATERIAL.

Having rejected the possibility of composite intrusion it may reasonably be assumed that the dykes were formed by a single intrusion of magma. It is evident from the textural relations that the pyroxene and almost all of the plagioclase crystallized after the intrusive motion had ceased. There is, however, no such indication of the stage at which the olivine and spinel crystallized other than that they were present as crystals when the pyroxene and plagioclase crystallized. Since chrome spinels occur as inclusions in olivine crystals the spinel must have crystallized before, or contemporaneously with, the olivine. There are three possible periods of formation of the olivine crystals :- (i) they were present in the magma before it was intruded, (ii) they crystallised from the magma during intrusion and (iii) they crystallized from the magma after the emplacement of the dykes.

Bowen (1928, p. 153) observed the remarkable "tendency towards idiomorphism" of the olivine crystals in the dykes and considered this to be of considerable significance since, in a magma containing as much olivine as many of the dykes, mutual interference would prevent the attainment of good crystal form. He therefore concluded that the olivine must have crystallized under more spacious conditions than existed in the dykes and consequently, must have been present before the dykes were intruded.

In all the dykes a proportion of the olivine crystals contain translation lamellae (chapter V.2.b). The various theories which have been advanced to account for translation lamellae (see chapter XVII) all require the subjection of the crystals to pressure under conditions which appear unlikely to have prevailed in the dykes during or after intrusion.

The sizes of the plagioclase and pyroxene crystals vary from one dyke to another and frequently within individual dykes but the range of sizes of olivine crystals is relatively constant throughout each dyke and throughout the group. The implication is that although the crystallization conditions varied from dyke to dyke and locally within dykes the olivine was unaffected by these variations, i.e. the olivine was in a crystalline state when the dykes were intruded.

The above evidence appears to preclude both the possibility that most of the olivine crystallized after the emplacement of the dykes and the possibility that it crystallized during the intrusion of the dykes. Further evidence (considered below) precludes only the possibility that the olivine crystallized after the emplacement of the dykes.

Many of the dykes have fine-grained margins and in some cases they are actually chilled against the country rock. According to Drever and

Johnston (1957, p. 309-310) the rapid crystallization of olivine which would be expected from a picritic magma at such contacts would result in the development of skeletal crystals. Since skeletal olivine crystals are extremely rare in the dykes and are no more abundant in the margins of the dykes than in the centres (chapter V.2.b) it appears that the olivine crystals must have been present before the marginal chilling occurred.

The fact that olivine crystals became wedged in the entrances to the smaller offshoots (chapter V.2.j) is consistent with this conclusion.

In considering the stage at which the olivine crystallized, one important factor is the differentiated state of the dykes. In all the dykes for which mineral distribution curves have been prepared (except dyke 2, which is discussed below) the plagioclase and pyroxene contents vary sympathetically with each other and antipathetically with the olivine content. It is thus apparent that the absolute amounts of pyroxene and plagioclase which crystallized from the magma at any point in a dyke were controlled by the amount of olivine already present at that point and therefore, the differential distributions of olivine crystals were established before the plagioclase and pyroxene crystallized. If the olivine crystallized in the dykes after emplacement it must be assumed that initially it was uniformly distributed throughout each dyke. Two processes which might have caused differential distribution of the olivine crystals subsequent to emplacement are gravitative accumulation, as proposed for the

Palisade sill by Walker (1940, p. 1083-1089), or gravitative accumulation plus convection currents, as proposed for the Skaergaard intrusion by Wager and Deer (1939, p. 262-270). The possibility of gravitative accumulation is, however, eliminated by the fact that the differentiation process has evidently operated in a lateral rather than vertical direction. Various complex patterns of convection cells within the individual dykes might produce olivine distributions such as those observed but, apart from the obvious objections to such a mechanism, it appears to be extremely unlikely that convection currents could arise in such small intrusions. [Walker (1956, p. 440) considered that convection currents would have been negligible in the 1000 foot thick Palisade sill and magma chambers in which such currents are believed to have existed are of the order of thousands of metres deep (Wager, 1963, p. 5; Carr, 1954, p. 371).]. Although the writer is unaware of any other process which could have produced the observed differential distributions of olivine crystals after the emplacement of the dykes there is at least one process (discussed in the following section) which could have produced such differentiation during intrusion. It therefore appears probable that the differentiation occurred during the emplacement of the dykes and this is consistent with the conclusion that the olivine crystals must have been present in the dykes before their emplacement.

It can only be concluded from the evidence presented above that all or most of the olivine crystals were present in the magma before the intrusion of the dykes. It is, however, possible that a small proportion of the olivine crystals, which exhibit neither translation lamellae nor idiomorphism, may have crystallized after the emplacement of the dykes.

3. FLOWAGE DIFFERENTIATION.

It has just been concluded that the dykes were intruded as suspensions of olivine crystals and ultrabasic rock fragments (the xenoliths) in a liquid from which pyroxene, plagioclase and possibly a little olivine subsequently crystallized. Since the observed distributions of the olivine crystals within these suspensions could not have arisen after emplacement they must have been formed prior to or during the emplacement of the dykes. The possibility of any pre-intrusive distribution of the solid phases remaining relatively undisturbed during intrusion appears remote, and it is the writer's contention that the differentiation occurred during the intrusion of the dykes.

It now remains to be shown that the evidence already presented can be interpreted as indicative of differentiation during laminar flow of a viscous medium in which solid particles were suspended.

The olivine content varies across the dykes and it is therefore evident that the differentiation involved transverse movement of the suspended olivine crystals within the liquid. The migration of suspended particles in flowing viscous media has been investigated by workers in fluid mechanics and its applications in industry and medical science have been extensively studied in recent years. However, until Bhattacharji and

Smith (1964) invoked it to account for the central picritic zone of the Muskox feeder dyke, flowage differentiation had not been acknowledged as a petrological process, although Flett (1931, p. 154-155) suggested that differentiation could occur during intrusion.

Bhattacharji and Smith (1964, p. 151-152) concluded from their experiments on a scale model of the Muskox feeder dyke that, under the conditions which prevailed in that dyke, olivine crystals suspended in a basic magma would migrate towards the centre of the dyke during intrusion. The physical laws governing motion of suspended particles during flow of a viscous medium are not well understood and conflicting results have been obtained under different flow conditions. Before extrapolating the results of Bhattacharji and Smith to the dykes of south-west Skye, it is necessary, therefore, to review the results of other works concerned with the flow of suspensions.

At speeds below the regime of turbulent flow two types of flow can occur, namely plug flow and laminar flow. In plug flow there is no movement of the suspended particles relative to each other and no concentration of the particles after the initial development of a particle-free layer of the suspending medium between the conduit walls and the plug of suspended material. This type of flow has frequently been recorded in aqueous suspensions of wood pulp fibres etc. (Forgacs et al., 1958; Baines, 1958) and has been shown to be associated with the ability of the flexible fibres to form continuous networks (Goldsmith and Mason, 1964, p. 464). Thus, while plug flow might occur in magmatic flow systems containing high concentrations of fibrous or elongated crystals, it appears to be improbable in suspensions of the type occurring in the dykes except at very high velocities and particle concentrations. In laminar flow there may be both continuous movement of the particles relative to each other and concentration of the particles. In the present investigation particular attention is paid to this type of flow.

Probably the earliest work on the flow of suspensions was that of Poiseuille (1836) who observed that the corpuscles in flowing blood tended to keep away from capillary walls. Since then, much further work has been done and the results of some of the more recent, relevant investigations are summarized below.

Starkey (1955; 1956) and Scott-Blair (1958) suggested that solid particles suspended in a flowing viscous fluid would migrate towards the axis of the conduit. Segré and Silberberg (1961; 1962) studied the motion of small neutrally buoyant particles during flow in a cylindrical tube and concluded that suspended spherical particles tended to migrate towards concentration maxima at distances of 0.6 of the tube radius from the axis. This is known as the tube pinch effect. In their experiments, the Reynolds number of the tube* ranged from 0 to 30 and the Reynolds number of the particles** was less than 1.

Bretherton (1962) concluded from a theoretical study that, when

*[$Re = \frac{pVR}{u}$ where p = density of the fluid, V = mean velocity of the fluid, R = tube radius and u = viscosity of the fluid]

**[$Re_p = \frac{pVr}{u}$ where p = density of the fluid, V = mean velocity of the fluid, r = the radius of the particle and u = the viscosity of the fluid].

the Reynolds number of the tube is small, rigid bodies of revolution would not migrate towards the axis although particles of extreme asymmetrical shapes may do so. However, Bretherton did not consider the effect of inertia of the fluid which, according to Segré and Silberberg, produces migration. Oliver (1962) found that solid particles of a higher density than the suspending fluid moved towards the conduit walls during downward flow whereas those less dense than the fluid migrated axially. Goldsmith and Mason (1964) observed that suspended solid particles with Reynolds numbers below 10^{-6} maintained a constant position relative to the tube walls during flow but that fluid droplets migrated towards the axis. Saffman (1965) calculated that, during upward flow, solid particles denser than the suspending fluid would migrate towards the axis and those less dense than the fluid would migrate towards the walls of the conduit. His calculations were for tube Reynolds numbers greater than 1 and particle Reynolds numbers much less than 1.

Jeffrey and Pearson (1965) concluded that, during upward flow, neutrally buoyant particles would behave as observed by Segré and Silberberg, particles denser than the fluid would migrate towards the axis of the conduit and particles less dense than the fluid would migrate away from the axis: the opposite would apply during downward flow.

It appears reasonable to assume that, while the intrusive flow of the dykes was mainly longitudinal, it was also in an upward direction. Due to the impossibility of determining precise values of velocity, viscosity, etc. the Reynolds numbers of the dykes [i.e. the "tube"

Reynolds numbers for the dyke flow system] cannot be calculated, but they were probably in the range 1 to 50 (cf. Bhattacharji and Smith, 1964, p. 151). The Reynolds numbers of the suspended olivine crystals were undoubtedly much less than 1 but were probably greater than 10^{-6}. [According to Bhattacharji and Smith (1964, table 1) Re_p (olivine crystals) $\approx 10^{-3}$ to 10^{-2} in the Muskox feeder dyke]. Many of the above works were concerned with relatively dilute and single particle suspensions and the results may not be valid for concentrated suspensions of the type involved in the formation of the dykes. Since the well-understood laws of fluid mechanics are not rigidly applicable at high particle concentrations no attempt is made to consider the flow systems in the dykes quantitatively, but several qualitative aspects of the intrusive flow of the dykes are discussed below.

Although of little relevance to the present discussion on dykes, it is worth noting that the opposite effects of upward and downward flow (Oliver, 1962; Saffman, 1965; Jeffrey and Pearson, 1965) necessitate extreme caution in invoking any form of flowage differentiation to explain crystal concentrations in sub-horizontal bodies such as sills and sheets. Plug flow, however, undoubtedly can occur in horizontal conduits and, although it has been suggested above that very high velocities and crystal loads _may_ be necessary, there is no apparent reason why it should not occur in sills and sheets. In addition, Simkin (1967) has concluded that a differential distribution of olivine crystals in basic magma established during the uprise of the magma in a vertical conduit can be preserved when the conduit bends to form a sill.

According to Starkey (1962) and Bhattacharji and Smith (1964), particles migrate axially because the velocity profile for laminar flow of a viscous fluid in a conduit is a parabola which equals zero at the walls. The suspended particles, other than those located exactly in the centre of the conduit, are therefore subjected to velocity gradients which cause rotation and axial migration of the particles.

As axial migration proceeded during flow, the margins of an initially homogeneous suspension would become progressively impoverished, and the centre correspondingly enriched, in solid particles. If this process operated in the dykes and flow ceased before all the olivine crystals had migrated away from the edges of the dyke, the concentration of olivine crystals would increase gradually towards the centre of the dyke, i.e. a type (i) olivine distribution (chapter Vl. 2. g) would occur. The olivine distribution curve for dyke 29 (Fig. 62), therefore, indicates that the dyke could have been differentiated in this manner if flow ceased shortly after the extreme edges of the dyke had been almost completely evacuated of olivine crystals.

If the process was prolonged, presumably involving flow over long distances, all the crystals should migrate into the centre of the conduit leaving the marginal regions free from crystals. In practice a small proportion of the crystals would probably remain disseminated throughout these regions. The central picrite zone in the 37 mile long Muskox feeder dyke (Smith and Kapp, 1963, p. 31) has apparently been formed in this way. The sharp junction between the picrite and norite

(Bhattacharji and Smith, 1964, p. 150), however, appears to be anomalous since, in theory, flowage differentiation should produce gradual changes in olivine content and sudden changes could only be produced by plug flow or by composite intrusion (chapter XI. 1). The possibility that plug flow might have become established in the central part of this dyke, due to its high crystal content relative to the margins, cannot be disregarded despite the conclusions of Goldsmith and Mason (1964, p. 464) (above). Although it is shown below that laminar flow can occur in the Ben Cleat dykes at olivine crystal concentrations much higher than the 40-50% in the Muskox picrite, the higher velocity in the centre of the much wider Muskox feeder dyke may have favoured plug flow. In addition, the experimental results of Bhattacharji and Smith (1964, fig. 3) seem to indicate a tendency towards plug flow rather than laminar flow since the margins of the conduit appear to be completely free from particles in the advanced stages and the "filament" has a sharp edge.

Olivine distributions of type (ii), such as that in dyke 9 (Fig. 61), are similar to those of type (i) except that the olivine content is relatively constant in the central part of the dyke. The levelling out of the olivine distribution curve in the axial region of the dyke could be due to either of the two factors discussed below and, consequently, dykes with this type of olivine distribution could also have been differentiated during the intrusive flow.

Goldsmith and Mason (1964, p. 470-471) have demonstrated that above a certain concentration of suspended solid particles (38% in their experiment) the velocity profile becomes blunted and is no longer perfectly parabolic. If the velocity profile of the flowing dyke material became blunted in the same way, with a tendency towards plug flow in the centre, there would have been little or no velocity gradient in the axial region of the conduit and inward migration of olivine crystals would have become negligible or ceased when the critical concentration was reached. The resulting olivine distribution curve would level out at approximately the limiting concentration. While the limiting concentration would vary from one flow system to another, it seems significant that the olivine content at which the distribution curve for dyke 9 levels out is almost 30% higher than the maximum olivine content of dyke 29. [The olivine distribution curve for dyke 29 does not level out].

Another possibility is that a limiting concentration of olivine crystals existed above which mutual interference prevented further packing of the crystals. In plutonic intrusions gravitative accumulation of crystals can produce almost monomineralic rocks, either by adcumulus growth (Wager <u>et al</u>., 1960, p. 77-81) or by the squeezing out of the interprecipitate liquid by the superincumbent load. In the dykes, however, there is no evidence of the action of the former process and the latter could not have operated. The forces producing concentration of the crystals in the dykes during flow were undoubtedly small compared with superincumbent load pressures in plutonic intrusions but the longitudinal motion and particle rotation would assist in the packing of the crystals, and it appears that concentrations of olivine crystals greater than 70%

have been formed in the dykes during flow.

Olivine distribution curves of type (iii), such as those for dyke 6 (Figs. 59 and 60), have two maxima. Bimodal concentrations of this type could arise in either of the following ways :-

During laminar flow the velocity gradient is greatest at the walls of the conduit and smallest at the axis. Since migration depends on this gradient, particles would be arriving at any point between the axis and the walls more rapidly from the margins than they would be departing towards the centre. From an initially homogeneous suspension this would produce two small concentration maxima, one near each wall of the dyke, which would gradually increase as they migrated towards the axis. However, as axial migration progressed, the distribution of the particles would become non-uniform and fewer particles would be arriving from the margins than were departing towards the axis thus disrupting the double maxima and eventually establishing the single maximum observed in many of the dykes. Theoretically disruption of the bimodal distribution should occur shortly after the suspension became non-uniform, and bimodal olivine distributions could therefore represent only a very early stage in the formation of the differentiation pattern of the dykes. If this is the case olivine distributions such as that in dyke 6 represent too advanced a differentiation stage to have originated in this way. However, migration of the olivine crystals was almost certainly a very slow process and it may be that the difference between the number of crystals arriving and the number departing would be too small to affect the slow build-up of crystals until the distribution became more uneven than in dyke 6. The fact that Bhattacharji and Smith did not record a similar early stage in the development of their crystal column cannot be regarded as a valid objection to the above hypothesis since they commenced flow with a basal accumulation of particles (Bhattacharji and Smith, 1964, fig. 3) rather than an evenly disseminated suspension, as did Segré and Silberberg (1962, p. 116). Even in the event of the dykes having originated from a gravitative accumulation of olivine crystals in a magma chamber it appears very unlikely that the olivine accumulate could have been introduced into the dyke fissure without becoming thoroughly mixed with the liquid. The principal objection to the above hypothesis is that, if the magma flowed outwards from the centre of the Cuillins, as suggested in chapter XVII, dyke 6 must have flowed further than most of the dykes and, consequently, the olivine distribution in this dyke should represent a more advanced stage of differentiation than those in most of the other dykes rather than a more embryonic stage. However, it is evident from the relatively small difference between the olivine contents of the margins and the centre of the dyke that it does not represent an advanced stage, and it may be concluded that the differentiation process was comparatively inefficient in dyke 6. This could have been caused by a slower rate of flow.

The alternative explanation, which does not imply that olivine distributions of type (iii) are embryos of types (i) and (ii), is suggested by the results of Segré and Silberberg. If the olivine crystals were neutrally buoyant instead of being denser than the liquid, olivine distributions of type (iii) could have been formed by the tube pinch effect. It may have been that if cooling increased the viscosity and density of the liquid during flow, the difference between the densities of the crystals and liquid became less significant and the behaviour of the crystals approached that of neutrally buoyant particles. However, this appears less likely than the first hypothesis since very small differences in density are sufficient to produce axial migration (Jeffrey and Pearson, 1965, p.721). In addition, Starkey (1962) has suggested that tube pinch would not occur at high particle concentrations and, in any case, it is suggested below that any cooling which occurred during the intrusion of the dykes must have been slight and confined to the marginal parts of the dykes.

Although neither of the hypotheses tentatively proposed above is entirely satisfactory, it is evident that bimodal olivine distributions are a modification of the differential distributions of olivine crystals formed during the intrusive flow of the dykes.

In distributions of types (iv) and (v) the olivine content decreases away from the contacts before increasing towards the centre of the dyke. Marginal decreases of this type can readily be explained by considering the effects of marginal cooling on the flowing magma. Although it is concluded in chapter XVII that the dykes underwent very little cooling during intrusion, it is evident that any cooling which did occur would be greatest at the edges of the dykes where the magma was in contact with the country rock. As the margins were cooled and the liquid became more viscous it would have become increasingly difficult for the olivine crystals to migrate away from the edges of the dyke. [An increase in viscosity decreases the particle Reynolds number thus suppressing axial migration of the particles (cf. Goldsmith and Mason, 1964)]. Once the differential distribution of olivine crystals was established in the flowing dyke material, marginal cooling would have little effect on the eventual distribution of olivine since most of the crystals would already have migrated away from the margins. However, near the source of the dyke, where the suspension must have been almost homogeneous, the extreme edges of the dyke would probably have retained most of the olivine crystals. In both cases flowage differentiation would have been unimpeded in the central part of the dyke which was virtually unaffected by marginal cooling during intrusion. According to this hypothesis, olivine-rich margins should only occur relatively near the source of the dykes. If, as proposed in chapter XVII, the source was the Sgurr Dubh ultrabasic intrusion, the olivine distribution curve for dyke 31 in Coir' a' Ghrunnda can be explained in this way. Both margins of dyke 31 contain the same amount of olivine and this amount is approximately equal to the average olivine content of the dyke. This implies that the olivine content of the margins represents approximately (see below) the original concentration of olivine crystals in the homogeneous suspension.

Dyke 2, which has a type (v) olivine distribution, occurs a long distance from the Sgurr Dubh intrusion and appears to disprove the hypothesis of marginal cooling. The field relations, however, suggest that dyke 2 is an offshoot of the larger dyke 1 (chapter V. 1.a) and has, therefore, flowed as a separate dyke for a comparatively short distance. If, as the field relations suggest, the material which formed dyke 2 was drawn-off from the south-west side of dyke 1, and if this withdrawal occurred after the differential distribution of olivine crystals was established in dyke 1, dyke 2 should contain less olivine than the centre of dyke 1. This is in accord with the observed olivine contents. The suspension which entered the offshoot would have been relatively homogeneous since it was all drawn from approximately the same part of the parent dyke. Whatever the initial distribution in this suspension, a new differential distribution of olivine crystals would have been established in dyke 2. The suggestion that dyke 2 is an offshoot from dyke 1 is therefore consistent with the relatively slight degree of differentiation exhibited by dyke 2 (Fig. 58), and the olivine-rich margins can thus be accounted for by the above hypothesis.

The olivine distributions in the dykes differ from the ideal cases, illustrated in Fig. 64, principally in their lack of symmetry about the axis of the dyke. The writer is at present unable to offer an explanation of this asymmetry and can only suggest that the velocity profiles themselves may not have been symmetrical. Asymetrical flow might have been induced in the flowing magma by bends or irregularities in the dyke walls. No asymmetry has been recorded in any of the experimental flow systems studied by the writers listed above, but these systems all involved flow between parallel planar walls, or in smooth straight tubes.

Bhattacharji and Smith (1964, p. 153) suggested that if crystallization took place during flow the early formed crystals would be concentrated in the centre of the dyke thus producing a cryptic variation. The Mg:Fe ratios of the olivine and orthopyroxene, and the anorthite content of the plagioclase, increase towards the centre of the Muskox feeder dyke in accordance with this theory. According to Jeffrey and Pearson (1965) this could only occur if all the particles (in this case the crystals of all three minerals) were denser than the liquid. If crystals of any mineral were less dense than the suspending fluid a reversed cryptic zoning of that mineral should occur.

In the dykes with which this research is concerned only olivine and occasionally a little plagioclase were involved in the flowage differentiation. There is no doubt that the olivine crystals were denser than the liquid but the relative densities of the plagioclase crystals and the liquid cannot be determined with such certainty. It has been suggested (von Eckermann, 1938) that plagioclase crystals may rise in basic magma, but gravitative sinking of plagioclase crystals has frequently been proposed as a differentiation mechanism of basic magma (e.g. Richey and Thomas, 1930, p. 96; Wager and Deer, 1939, p. 262-263). Hess (1960, p.85) concluded that "plagioclase probably would not have floated upward, but might have settled or remained suspended" in the Stillwater magma. Brown (1956) and Wadsworth (1961) have proposed that crystals of calcic bytownite settled as a cumulus phase during the formation of the ultrabasic rocks of Rhum. Since these rocks are similar in composition to the dykes, it appears probable that the plagioclase crystals in the dykes were also denser than the liquid.

Because all or almost all of the olivine crystals were present in the dyke material prior to intrusion no cryptic variation in the composition of the olivine crystals should exist. It is evident from Table 16 that this is the case. The plagioclase distribution curve for one of the dykes, dyke 2, indicates that plagioclase crystals migrated away from the extreme edges of the dyke during flow. The migration of plagioclase crystals was probably confined to the marginal parts of the dyke because the crystallization of the plagioclase commenced at the cooler edges of the dyke and, as the textural relations indicate, flow ceased very shortly after plagioclase began to crystallise. Although crystallization and axial migration of the plagioclase occurred contemporaneously, it appears improbable that a cryptic variation in the composition of the cores of the plagioclase crystals, of the type suggested by Bhattacharji and Smith, would exist in such small intrusions as the dykes and, in any case, the number of crystals removed from the parent liquid would not have been sufficient to effect any significant change in the composition of the liquid. The uniformity in the composition of the cores of the plagioclase crystals throughout the dykes (Table 18) apparently confirms this hypothesis.

The introduction of plagioclase crystals from the extreme edges into parts of the dyke in which crystallization had not commenced may also be responsible for the existence of "pseudo-phenocrysts" as introduced crystals would have had longer to grow than those which crystallized entirely in their present position by the time growth was curtailed by mutual interference. It may be significant in this connection that, of the dykes for which modal profiles have been prepared, dyke 2 is the only one which shows migration of plagioclase crystals and is also the only one in which "pseudo-phenocrysts" occur in the margins. [Pseudo-phenocrysts occur in other dykes for which modal profiles have not been prepared, e.g. dyke 8].

Segré and Silberberg (1962, p. 145) observed a difference in the distributions of large and small particles and Bhattacharji and Smith (1964, p. 152) noted that "the rate of inward movement of solids increases with the particle size". A similar effect of particle size has been recognized by several workers including Vejlens (1938), and Karnis <u>et al</u>., (1963). Increases in olivine content should therefore be accompanied by increases in the average size of the olivine crystals in the dykes. Of the three determined transverse variations in the average length of the olivine crystals (chapter VIII) only in the case of dyke 6 does the curve correspond closely with the olivine distribution curve (cf. Figs. 59 and 67). The curves obtained for dykes 1 and 31 are anomalous in this respect and an attempt is made below to account for these anomalies.

The only significant difference between the transverse olivine size profile and the olivine distribution curve for dyke 31 is that the average length of the olivine crystals at the east contact is 0.1 mm less than that at the west contact (Fig. 68) whereas the olivine contents are the same at both contacts (Fig. 63). This appears to invalidate the previous suggestion that the extreme edges of this dyke represent the original homogeneous suspension, but such a small difference in size could have been achieved by the removal of a few more of the largest crystals from the east contact than from the west. If the actual number of crystals involved was small the contact rock would not differ greatly from the original suspension. It is evident from the asymmetrical nature of the olivine distribution curve that the flowage differentiation must have been more efficient at the east side of the dyke than at the west and this could have been responsible for the differential removal of olivine crystals from the two margins of the dyke. This migration was probably confined to the largest of the crystals because only they had a sufficiently high migration potential to overcome the effect of marginal cooling. Such selective removal would also account for the proportion of the olivine crystals involved being small.

The discrepancy between the transverse olivine size profile and the olivine distribution curve for dyke 1 (outcrop 1/10) is much greater than that for dyke 31. The distribution curve (Fig. 57) is slightly bimodal with the north-east maximum smaller than the south-west. The average length of the olivine crystals at the north-east contact is approximately 0.1 mm less than that at the south-west contact (Fig. 66). The size profile has a maximum corresponding to the north-east maximum of the distribution curve and a minimum corresponding to the south-west maximum of the distribution curve. Since marginal cooling of the dyke in outcrop 1/10 would not have affected the already established differential distribution of olivine crystals the difference between the average lengths of the olivine crystals at the two contacts cannot be explained in the same way as that in dyke 31. The existence of a size minimum is apparently a major anomaly.

It was observed in chapter V.1.a that dyke 1 is not vertical but dips steeply to the north-east. None of the other dykes for which size or distribution profiles have been prepared are far from vertical, and possible explanations of the above observations are forthcoming from the consideration of the effects of flow in a non-vertical conduit.

During upward flow in a vertical conduit the force exerted by gravity on a suspended solid particle which is denser than the fluid acts in the opposite sense to the force producing flow. Since the force due to gravity is small compared with the force producing flow it is easily overcome by the flow. However, in a slightly non-vertical conduit the force due to gravity is not exactly opposed to the viscous drag acting along the conduit, but acts in the direction (G) illustrated in Fig. 77. This force can be resolved into a component acting parallel to the walls of the conduit (g^1) and another acting perpendicular to the walls (g^2). As in a vertical conduit, the viscous drag acting along the conduit (F) is much greater than the force due to gravity and g^1 is easily overcome by F with little or no effect on the flow. However, the force (f) which produces axial migration of the particles during flow is small compared with the force F and the effects of g^2 on this

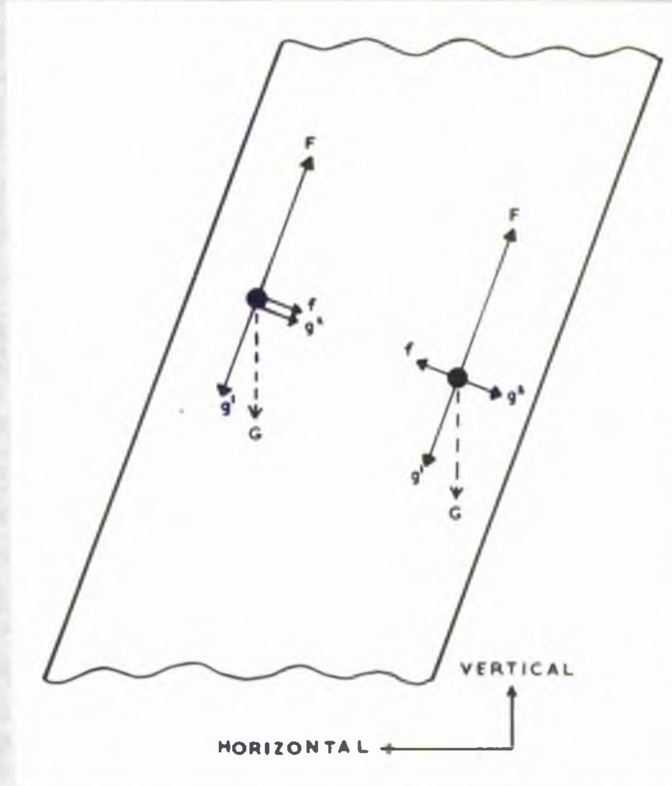

Fig. 77. Schematic diagram of the forces acting on a particle during upward flow in a non-vertical conduit.

force cannot be ignored.

The component g^2 acts in the same sense whatever the position of the particle relative to the walls of the conduit, but the force f acts in opposite senses on opposite sides of the conduit axis. Consequently, in one half of the conduit (the left hand side in Fig. 77) f and g^2 act in the same direction and in the other (right hand side) they are directly opposed. The net result, therefore, is to increase the force producing axial migration of the particles in the left half of the conduit and decrease it in the right half.

When Fig. 77 is applied to outcrop 1/10 the left side of the figure corresponds to the north-east side of the dyke. There is no doubt that the material now forming dyke 1 in outcrop 1/10 flowed through a north-east dipping conduit as this part of the conduit is now occupied by the lower outcrops 1/1, 1/2 and 1/3 in all of which the dyke dips to the north-east. It can be seen from the olivine distribution curve (Fig. 57) that the north-east contact of the dyke in outcrop 1/10 contains less olivine than the south-west contact and that the concentration gradient is steeper in the north-east half of the dyke than in the south-west half. These observations appear to confirm that the axial migration of olivine crystals was more efficient in the north-east half of the dyke than in the south-west half. Since the migration potential of a particle is directly proportional to its size, the residual olivine crystals at the north-east margin should be smaller than those at the south-west margin. It can be seen from Fig. 66 that this is the case.

The olivine distribution curve for outcrop 1/2 (Fig. 56), on the other hand, indicates that flowage differentiation was more efficient in the south-west half of the dyke and it can only be suggested that this is due to the unexposed part of the dyke to the north-west of outcrop 1/1 having a reversed (i.e.south-west) dip. This, however, does not invalidate the above hypothesis since it is the dip of the part of the conduit through which the material flowed which governs the differentiation rather than the dip of the part in which flow stopped.

The velocity gradient, and consequently the axial migration, decrease towards the centre of a dyke. Where there is no transverse component of gravity, i.e. in a vertical conduit, or where such a component assists axial migration, e.g. the north-east half of dyke 1 in outcrop 1/10, small velocity gradients are probably capable of causing even the smallest particles to migrate. In the dykes, therefore, axial migration of all sizes of olivine crystals may persist until relatively close to the axis. On the other hand, where the crystals have to migrate against a component of gravity, e.g. the south-west half of outcrop 1/10, it is possible that, at a point some distance from the axis, the velocity gradient would have decreased to a level at which it was incapable of moving the smallest crystals. The number of the smallest crystals left behind would thus increase away from the wall reaching a maximum at the point beyond which they could not migrate. As lateral translation progressed the size of the crystals which could migrate no further would increase. Beyond the maximum concentration of smallest crystals, therefore, the size of the crystals left behind would become greater, and the resulting crystal size profile would be similar to that for the olivine crystals in the south-west half of dyke 1 in outcrop 1/10. It has already been observed that where there is the concentration of the smallest crystals the olivine content is a maximum. This is probably due to the increased packing potential of small crystals and, in addition, close packing may have been made more efficient by the flow-induced rotation aiding the relatively small translational force. The slightly bimodal nature of the olivine distribution curve and the anomalous transverse olivine length profile may thus be tentatively attributed to the non-vertical nature of the dyke.

It was concluded in chapter IX.2.c that the width of a dyke exerted a fundamental control on the olivine content of the centre of the dyke. In order to attempt to define this control it is necessary to consider the effect on laminar flow of varying the width of the conduit.

If the dykes originated approximately contemporaneously from the same magma chamber it may be assumed that, for each dyke, the olivine content of the parent material and the composition and viscosity of its liquid phase were the same or very similar. If the pressure in the magma chamber which resulted in the intrusion of the dykes was due to the superincumbent load it would have been relatively constant. A slight release of pressure might have accompanied the emplacement of each dyke but compared with the total pressure it would probably have been insignificant. If the viscosity and pressure are constant the effect of increasing the width of a conduit is to increase both the absolute velocity of flow in the centre of the conduit and the velocity gradient in the margins.

The simplest explanation of the observed relationship between the width of a dyke and the olivine content of its centre is that the increase in velocity enabled the liquid in the centre of the dyke to carry greater suspended loads of olivine crystals. There are, however, two important objections to this hypothesis. Firstly, the transport potential of a flowing liquid is directly proportional to a relatively high power of the velocity, and very small increases in width would therefore produce very large increases in transport potential. There is no evidence of a relationship of this type in the dykes. Secondly, even the narrowest of the dykes were evidently capable of carrying xenoliths, which were much larger than the olivine crystals and, consequently, they must have been able to carry concentrations of olivine crystals considerably in excess of those observed. It appears, therefore, that all the dykes were capable of carrying greater loads of olivine crystals than were available. This is consistent with the view that the parent material of each dyke was identical.

A more satisfactory explanation of the above relationship is that it is a result of flowage differentiation. In the margins of wider dykes the velocity gradient, and hence the differentiation, would have been greater than in the corresponding parts of narrower dykes. As a result, the degree of concentration of olivine crystals in the centre of a dyke at the expense of its margins would have increased with the width of the dyke. This process would apparently result simply in a redistribution of the original olivine content and should not affect the average olivine content of the dyke. However, it has already been suggested that a proportion of the olivine crystals became lodged in the margins of the dyke during the early stages of differentiation. As the amount of olivine becoming lodged in this way would have been approximately the same for wide dykes as for narrow ones the average olivine content of a narrow dyke in an advanced stage of differentiation would have been lowered more than that of a wide dyke. As suggested previously, there was probably a limiting olivine content above which further concentration was negligible, hence the levelling out of the trend curve in Fig. 73.

In this chapter it has been established beyond reasonable doubt that the dykes were emplaced as magmatic suspensions of olivine crystals and that the differentiation of the dykes occurred during their intrusion. However, the validity of the mechanism of intrusion and differentiation tentatively proposed for the dykes is less certain since the laws governing flow of concentrated viscous suspensions of solid particles are not well-understood. Nevertheless, the mineral distributions and transverse crystal size variations observed in the dykes closely resemble those expected, from theoretical and experimental studies, to arise by flowage differentiation of the dyke magma during laminar flow. In addition, no other mechanism known to the writer could have produced differentiation of this type.

Flowage differentiation during intrusion of the dykes is therefore proposed as the mechanism responsible for imposing upon them their distinctive differentiation patterns.

XII. COGNATE XENOLITHS

1. VARIATION IN TYPE.

Examination of thin sections confirms the field observation that the same types of cognate xenolith occur in each of the dykes. Dyke 1 is a typically xenolithic dyke and the results of a quantitative study of the different types of xenolith occurring in it are presented below.

Several large blocks from the dyke were serially sectioned and thin sections of the 47 xenoliths encountered during this sectioning were prepared. This may not represent a statistically valid sample of the different types of xenolith because of the relatively small number examined. In addition, many of the xenoliths are very similar to the dyke rock and, therefore, a few of these may have been missed. Nevertheless, this sample is sufficiently large to give a good indication of the different types present and their relative abundances. Modal analyses of the 47 xenoliths are presented in Table 25 and are plotted in terms of their primary minerals in Fig. 78. In order to plot the analyses it was necessary to correct the primary mineral contents to 100% (see chapter VI.2.a).

Like the dykes, the xenoliths are composed of olivine, clinopyroxene, plagioclase and chrome spinel but, with one notable exception (see Table 25), they are less altered to secondary minerals than the dykes. It is evident from Fig. 78 that the diversity of types previously noted is due to considerable variations in the relative amounts of the three principal minerals. There is, however, a continuous range of compositions rather than two main types of xenolith as suggested by the field observations (chapter V.1.e). The cause of the erroneous field observation becomes evident when the

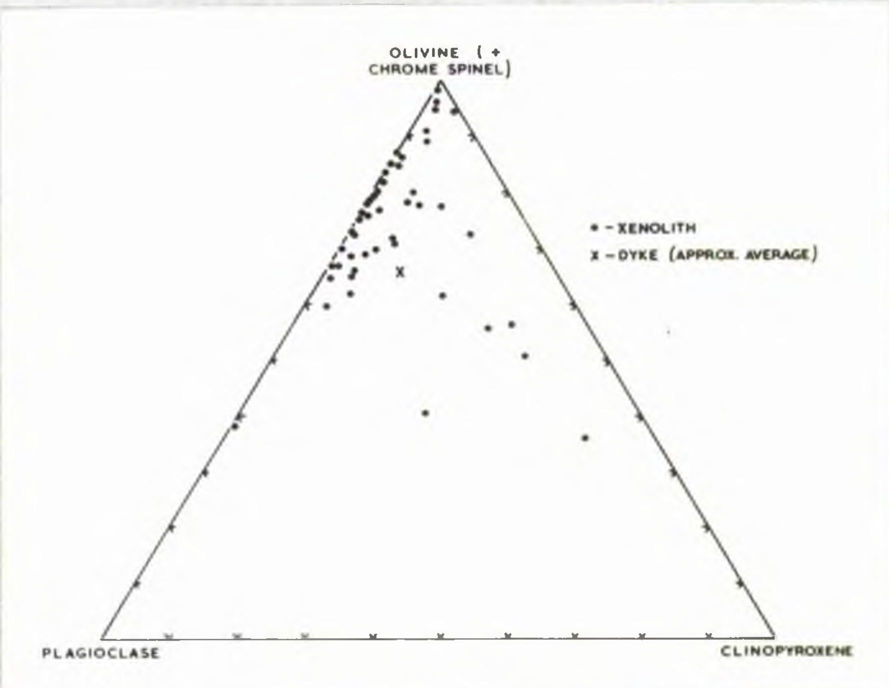

Fig. 78. Compositions of 47 xenoliths from dyke 1.

average composition of the host dyke is plotted in Fig. 78. Some of the xenoliths contain more plagioclase than the dyke and others contain less. Since the plagioclase crystals are generally larger than the majority of the olivine and pyroxene crystals in dyke 1 the xenoliths which are more felspathic are apparently coarser-grained than

TABLE 25.

Modal analyses of xenoliths from dyke 1.

% Olivine	% Pyroxene	% Plagioclase	% Chrome Spinel	% Secondary minerals
95.0	1.0	2.5	1.0	0.5
94.4	0.2	1.7	3.8	-
93.5	4.6	0.9	0.7	0.2
87.5	2.6	6.4	2.5	1.3
86.0	-	13.1	1.2	-
85.8	3.7	7.4	2.4	0.7
85.6	1.6	3.3	1.8	7.7
84.6	1.5	12.6	1.4	0.3
84.0	-	15.0	1.1	-
83.1	1.6	13.9	1.3	0.2
81.8	0.3	16.6	1.4	0.1
81.0	0.6	17.3	0.8	0.4
79.1	5.1	13.7	0.8	0.5
77.9	0.7	21.3	0.8	0.1
77.2	0.4	19.8	1.1	1.7
77.0	-	22.0	1.0	0.2
77.0	6.0	15.7	1.2	0.3
76.8	11.5	11.1	0.4	0.4
76.7	0.6	20.2	2.4	0.1
75.6	2.4	20.3	1.1	0.4
75.3	8.0	14.3	1.3	1.1
74.3	1.4	22.7	1.4	0.2
74.0	0.3	24.8	1.0	0.3
73.5	0.2	22.9	1.2	2.3
71.4	18.4	9.6	1.2	-
71.2	1.2	26.7	0.9	-
70.0	6.6	21.3	1.9	0.3
69.6	0.5	26.3	3.0	0.7
69.6	-	29.3	1.2	0.2
69.5	7.6	21.9	0.9	0.3
69.3	5.2	24.7	0.4	0.5
68.4	4.2	26.7	0.5	0.5
66.8	2.5	28.9	1.4	0.6
66.4	0.6	32.6	0.3	-
66.0	1.5	31.7	0.8	0.1
65.3	4.2	29.7	0.6	0.4
64.1	4.2	30.7	1.0	-
62.9	1.8	34.1	1.6	0.1
61.0	19.5	19.0	0.7	0.2
60.8	5.6	32.1	0.5	1.2
58.2	3.5	36.8	0.8	0.7
56.0	32.8	11.2	0.3	-
54.7	28.8	15.0	0.4	1.3
49.4	37.0	12.0	1.1	0.5
40.2	27.2	31.8	0.3	0.4
37.3	0.6	61.4	0.9	-
35.7	53.5	10.1	0.2	0.8

the dyke and those which are less felspathic are apparently finer-grained than the dyke.

Xenoliths of dunite or felspathic peridotite are most common. Peridotite xenoliths are less common and less than 10% of the xenoliths are picrite and allivalite. Although there is a compositional gradation between the types, they often differ in texture and grain-size, and brief petrographies of some of the principal types are given below.

There are two main sub-types of dunite xenolith. The first (Fig. 79) is composed of subhedral-euhedral olivine crystals which may be as long as 1 cm, although the majority are between 1 and 5 mm long.

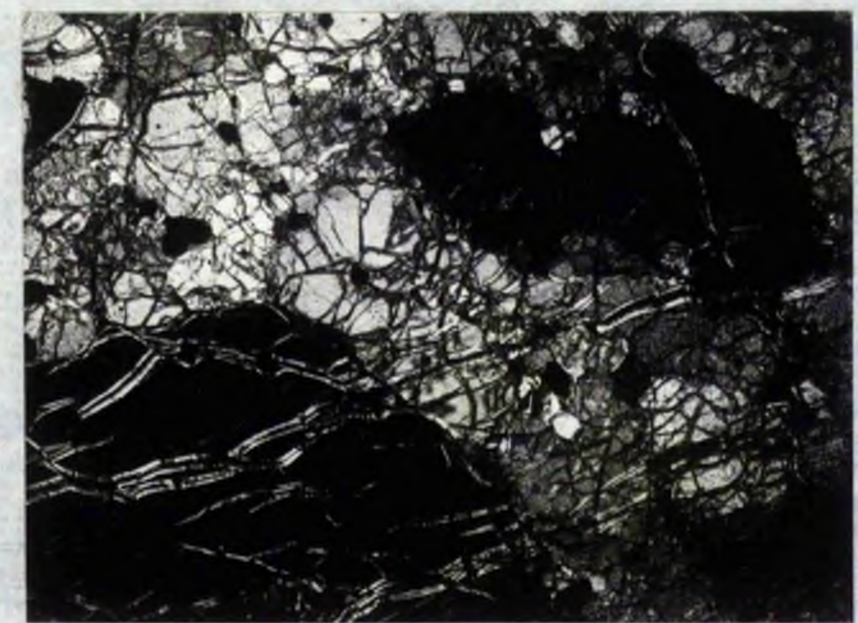

Fig. 79. Dunite xenolith from dyke 1. X 15; crossed nicols.

Translation lamellae are very common. Small amounts of plagioclase and clinopyroxene occur in the interstices between the crystals of olivine and spinel. In the second sub-type (Fig. 80) the olivine crystals are smaller, the largest being approximately 2 mm long. There are large

Fig. 80. Dunite xenolith from dyke 1.X 15; crossed nicols.

numbers of anhedral grains less than 0.2 mm in diameter which impart a granular texture to the rock. Apart from the differences in size and shape of the olivine crystals the two sub-types are similar. With an increase in plagioclase the dunites grade into felspathic peridotites.

The most abundant type of xenolith in the dykes is a felspathic peridotite containing between 70% and 90% olivine and less than 2% pyroxene. The olivine crystals are poikilitically enclosed by plagioclase crystals up to a centimetre long. They generally fall into one of four sub-types (la-ld), which can be distinguished by the size and shape of their olivine crystals, although xenoliths have occasionally been observed which are gradational between these sub-types. In the first sub-type (la) the euhedral-subhedral olivine crystals are mostly between 0.5 and 2 mm long and the elongate crystals exhibit a very strong parallelism (Fig. 81). The second sub-type (lb) is basically

Fig. 81. Felspathic peridotite xenolith (type la) from dyke 1. X 50; crossed nicols.

similar to the first, but the olivine crystals are larger (1 to 5 mm long) and the parallelism of elongate crystals is much less prominent (Fig. 82). The third sub-type (lc) exhibits no preferred orientation of the olivine crystals (Fig. 83), which are subhedral and between 1 and

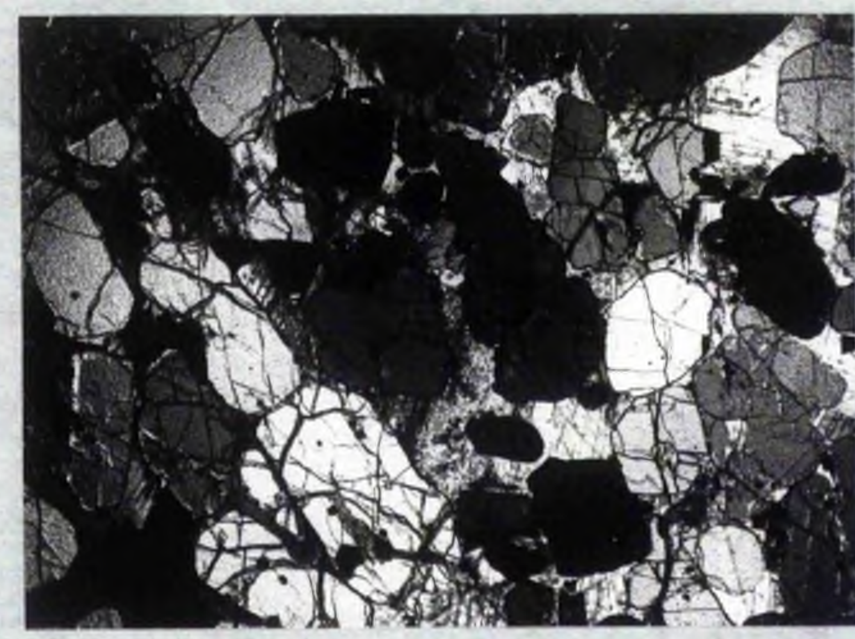

Fig. 82. Felspathic peridotite xenolith (type 1b) from dyke 1. X 15; crossed nicols.

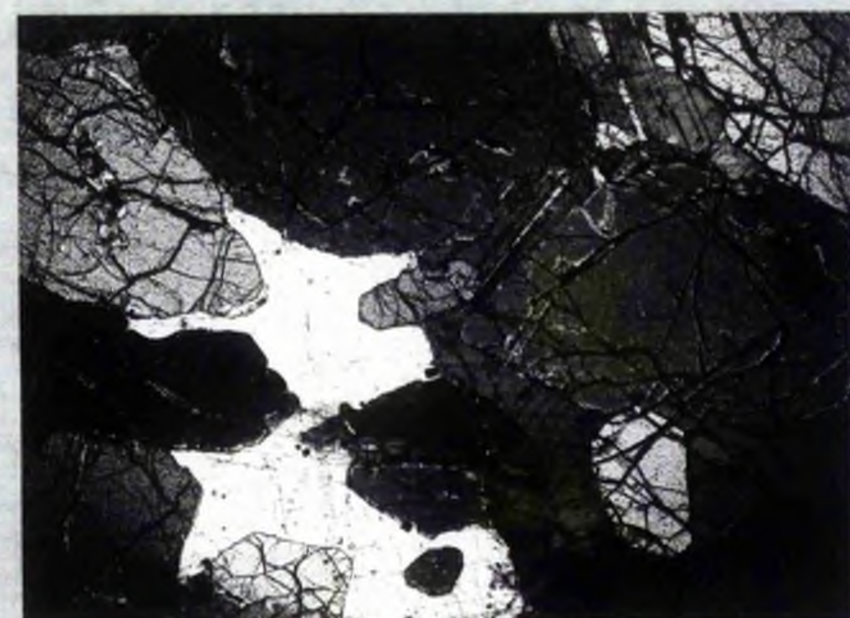

Fig. 83. Felspathic peridotite xenolith (type 1c) from dyke 1. X 15; crossed nicols.

5 mm long. In the fourth sub-type (1d) the olivine occurs mainly as anhedral grains less than 0.5 mm in diameter although a few larger subhedral crystals are also present (Fig. 84). Where the olivines in this type of xenolith are closely packed the rock appears to be transitional to the granular dunites described above. In all four sub-types the small amounts of pyroxene are insterstitial to the plagioclase crystals.

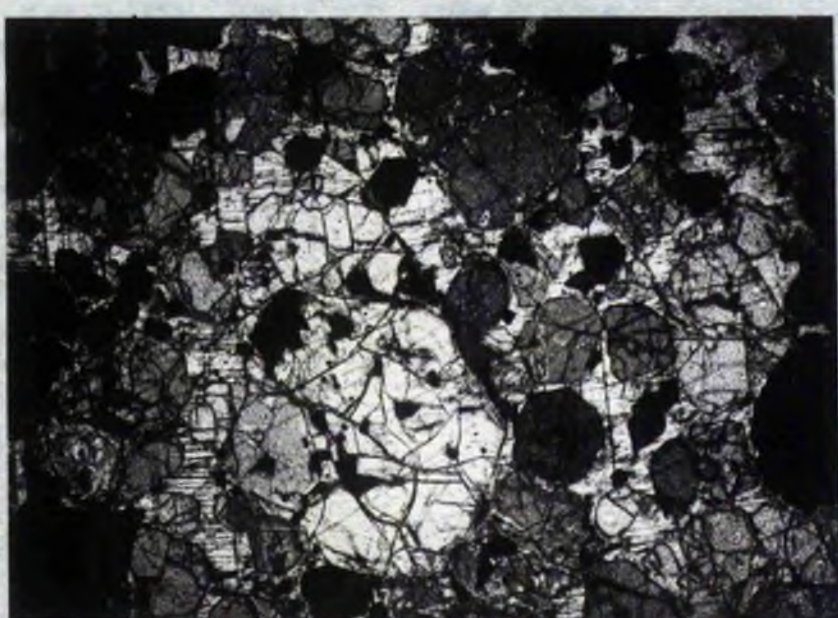

Fig. 84. Felspathic peridotite xenolith (type 1d) from dyke 1.X 15; crossed nicols.

A second type of felspathic peridotite xenolith (type 2) is also common in the dykes. This type contains more pyroxene than the first and with increasing pyroxene content grades into peridotite. Apart from the higher pyroxene content these xenoliths are similar to those of type 1: the plagioclase crystals are equally large and the same ranges of shapes and sizes of the olivine crystals are present. In examples transitional from type 1 felspathic peridotite, the interstitial pyroxene crystals are much smaller than the plagioclase crystals (Fig. 85). As the amount of pyroxene increases the crystals become larger and sub-ophitically intergrown with the plagioclase. These larger crystals frequently enclose olivine crystals poikilitically (Fig. 86). A felspathic peridotite xenolith of type 2 has been chemically analysed and the results are presented in Table 26.

TABLE 26

Chemical analysis and norms of a felspathic peridotite xenolith (type 2) from dyke 1

Analysis Wt.%		Norm Wt.%			Mineral compositions (normative)	
SiO_2	41.74	Qtz.		-	Plagioclase	
Al_2O_3	15.87	Or.		0.41	An.	94
Fe_2O_3	1.36	Ab.		4.43	Ab.	5½
FeO	5.50	An.		38.83	Or.	0½
MgO	22.55	Ne.		1.95		
CaO	9.08	Wo.	Di	2.54	Clinopyroxene	
Na_2O	0.95	En.	Di	1.96	Wo.	50
K_2O	0.07	Fs.	Di	0.32	En.	44½
H_2O+	1.64	En.	Hy	-	Fs.	5½
H_2O-	0.15	Fs.	Hy	-		
TiO_2	0.02	Fo.	Ol	37.97	Olivine	
CO_2	0.45	Fa.	Ol	6.76	Fo.	89
P_2O_5	0,02	Mt.		1.97	Fa.	11
Cr_2O_3	0.06	Il.		0.04		
MnO	0.10	Crt.		0.09		
Total	99.56	Ap.		0.05		

Analyst - F.G.F. Gibb

Fig. 85. Felspathic peridotite xenolith transitional between types 1 and 2. X 50; crossed nicols.

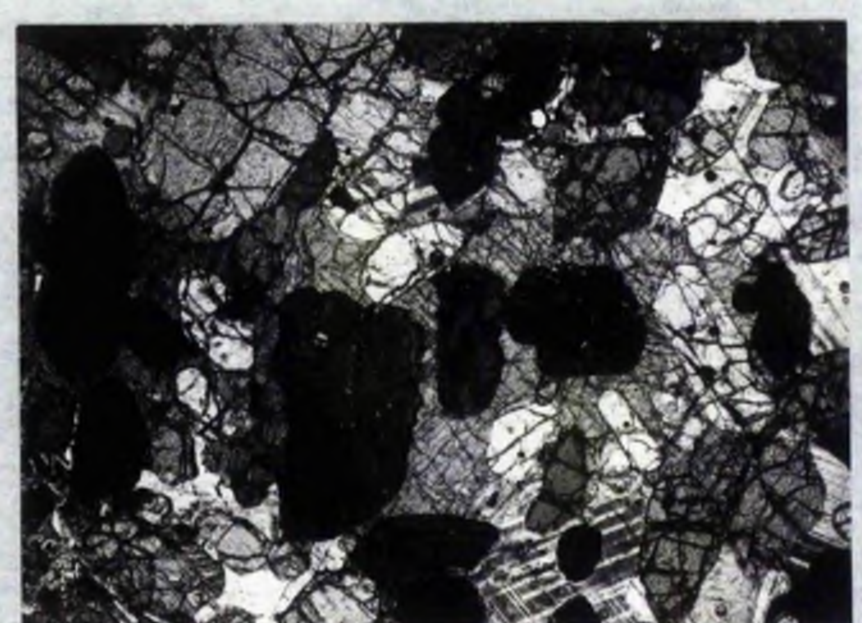

Fig. 86. Felspathic peridotite xenolith (type 2) X 15; crossed nicols.

Apart from the much higher Al_2O_3 and Na_2O and lower $FeO + Fe_2O_3$ and MgO, which are due to the higher plagioclase:olivine + pyroxene ratio of the xenolith, the principal difference between the analysed xenolith and its host rock (Table 24, analysis (i)) is the presence of nepheline in the norm.

The peridotite xenoliths are very similar to the felspathic peridotites but contain more pyroxene than plagioclase (Fig. 87). The pyroxene crystals may be as long as 1 centimetre and are sub-ophitically intergrown with the plagioclase crystals, which tend to be slightly smaller than those of pyroxene (i.e. the reverse of the relationship in the felspathic peridotites).

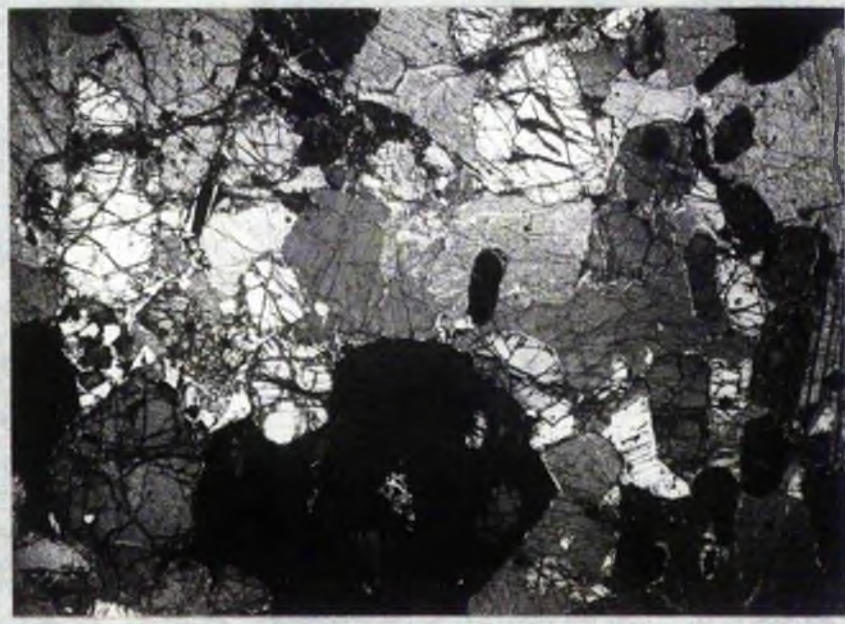

Fig. 87. Peridotite xenolith from dyke 1.X 15; crossed nicols.

The picrite xenoliths are mostly very similar to the type 2 felspathic peridotite xenoliths but contain less olivine. The olivine crystals are poikilitically enclosed by sub-ophitically intergrown crystals of plagioclase and pyroxene, which may be as long as 7.5 mm. Occasionally, small picrite xenoliths have been observed which are very rich in pyroxene and are almost olivine pyroxenites. These are generally less than an inch long and consist of a few very large crystals of greenish clinopyroxene poikilitically enclosing crystals of olivine and plagioclase which are between 0.5 and 2.5 mm long (Fig. 88).

Fig. 88. Pyroxene-rich picrite xenolith from dyke 1.
X 15; crossed nicols.

Xenoliths of allivalite (sensu stricto) are relatively rare, although many of the type 1 felspathic peridotite xenoliths approach allivalite in composition (Fig. 78). The allivalite xenoliths (Fig. 89) are composed of subhedral olivine crystals less than 1.5 mm long poikilitically enclosed by plagioclase crystals up to 7.5 mm long. A small amount of interstitial pyroxene is generally present.

There are two types of banded xenolith. They consist either of alternating bands of type 1 and type 2 felspathic peridotite (i.e. the difference is in the pyroxene content) or of bands of type 1 felspathic peridotite in which the olivine content varies from one band to another.

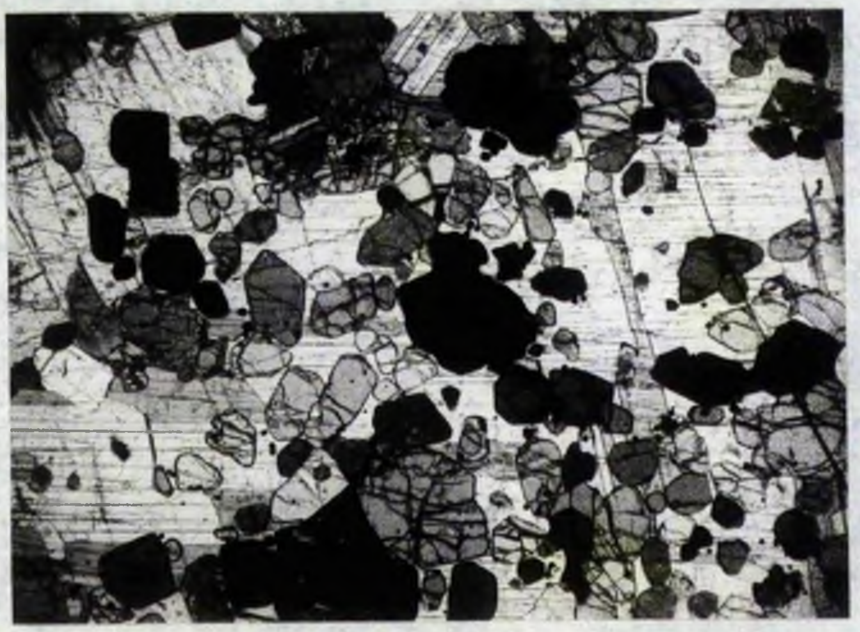

Fig. 89. Allivalite xenolith from dyke 1. X 15; crossed nicols.

The xenoliths are all relatively coarse-grained and the olivine contains abundant translation lamellae. The olivine and pyroxene crystals appear to be unzoned but the plagioclase crystals occasionally display very narrow, slightly zoned margins. It is evident that the various types of cognate xenolith are all closely related to each other and were undoubtedly derived from a common source.

2. MINERALOGY.

In thin section the olivine, clinopyroxene, plagioclase and chrome spinel forming the cognate xenoliths appear to be identical with the corresponding primary minerals in the dykes. The only notable exception to this is the greenish clinopyroxene in the pyroxene-rich picrite xenoliths. However, apart from the slight difference in colour [the pyroxene in the dykes is brownish] this pyroxene appears to be optically similar to that in the dykes.

The compositions of the principal minerals in an example of each of the two most abundant types of cognate xenolith have been determined optically. One of the xenoliths (i) is a felspathic peridotite of type 1 and the other (ii) is the felspathic peridotite of type 2 which has been chemically analysed (Table 26). The compositions of the minerals were determined by the methods employed for the minerals of the dykes (chapter VI. 1). The compositions of the olivine crystals in the two xenoliths are presented in Table 27. The difference in the compositions of the olivine in the two xenoliths is within the limits of accuracy of determination. The composition of the unzoned plagioclase

TABLE 27

Compositions of olivine in felspathic peridotite xenoliths from dyke 1.

Xenolith	$2V_{\alpha}$	$2V_{\gamma}$	$\frac{2V_{\alpha} + 180-2V_{\gamma}}{2}$	= % Fa	n_{β}	=% Fa	Composition
(i)	89.5°	87.2°	91.1°	11	1.671	9.5	$Fa_{10.3}$
(ii)	89.2°	87.2°	91.0°	11.5	1.673	10.5	Fa_{11}

crystals in both xenoliths is An_{85} and they are low temperature (plutonic) plagioclase. Xenolith (i) contains insufficient pyroxene for satisfactory optical determination of its composition but the pyroxene in xenolith (ii) has an optic axial angle ($2V_{\gamma}$) of 52° and an average n_{β} of 1.685 corresponding to a composition of $Ca_{43}Mg_{46}Fe_{11}$. Individual determinations of n_{β} ranged from 1.682 to 1.687. This is a slightly larger range than was obtained for the dyke pyroxenes and, if the crystals are all of the same composition, the determinative error is $\pm$ 0.003.

Although only the two representative xenoliths have been studied mineralogically, it appears probable from the results that the compositions of the minerals are relatively constant throughout the xenoliths.

The agreement between the optically determined and normative (Table 26) olivine compositions for xenolith (ii) is particularly good. From these and the corresponding compositions of the olivine in dyke 1 (Tables 16 and 24) it is evident that the olivine in the xenoliths is identical with that in the host dyke.

The high anorthite content of the normative plagioclase compared with the optically determined value is undoubtedly due to the presence of nepheline in the norm. The optically determined compositions of the xenolith plagioclases and the dyke plagioclase (Table 18) indicate that they are very similar if not identical. Like those of the pyroxene in the dykes, the normative and optically determined compositions of the pyroxene in xenolith (ii) differ considerably. The optically determined compositions of the xenolith pyroxene and the dyke pyroxene (Table 17) are identical (within the limits of determinative error).

On the basis of these determinations it may be concluded that the cognate xenoliths are formed of exactly the same minerals as the dykes. However, the possibility of very small compositional differences existing between the minerals of the various types of xenolith and those of the host dykes cannot be disregarded on the meagre optical data presented above. Such differences could only be detected by micro-analytical techniques, e.g. the electron probe micro-analyser, and are therefore outwith the scope of the present research. Since any such differences, particularly in minor element contents, would have an important bearing on the petrogenesis of the cognate xenoliths, the writer intends to study these in the course of future research.

3. RELATIONSHIP BETWEEN XENOLITHS AND THEIR HOST.

Because of similarities in grain-size and mineralogy between the xenoliths and dyke rocks it is often difficult to locate the boundaries of the xenoliths in thin section. However, where the enclosing dyke rocks are much finer-grained than the xenoliths, e.g. near the margins of most of the dykes, the junctions between the xenoliths and their hosts are readily discernible and the relationships between the xenoliths and the dyke rocks have been studied at a large number of these junctions.

The junction between the xenolith and the enclosing rock is invariably sharp. Crystals of all three of the principal minerals in the xenolith are frequently broken (Figs. 90 and 91) and the broken edges are in juxtaposition with the dyke rock. No evidence of reaction between the xenolith and dyke material has been observed and only occasionally do small veinlets of dyke rock penetrate the xenoliths. Very rarely a xenolith has been arrested in the process of breaking into two and a veinlet of dyke rock occurs between the semi-detached parts.

The presence of xenoliths composed partly of pyroxene and plagioclase in a magma from which identical minerals subsequently crystallized implies that the length of time the xenoliths were dispersed in the magma was insufficient to permit fusion of the pyroxene and plagioclase. The complete lack of corrosion at the edges of the xenoliths further implies that the time between the incorporation of the xenoliths in the magma and the onset of crystallization of the plagioclase from the magma must have been very short. In addition, it also suggests that the temperature of the intruded dyke material when the xenoliths were incorporated could not have been much higher than that at which crystallization of its plagioclase and pyroxene commenced.

Since the dyke rock is never chilled against the xenoliths the

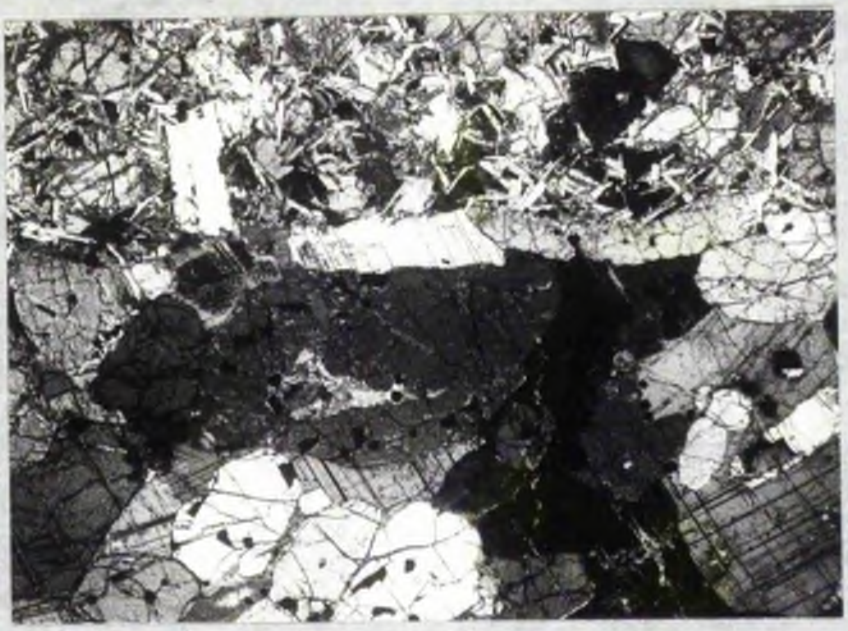

Fig. 90. Broken crystals of olivine and plagioclase at the contact of a xenolith with dyke rock. X 15; crossed nicols.

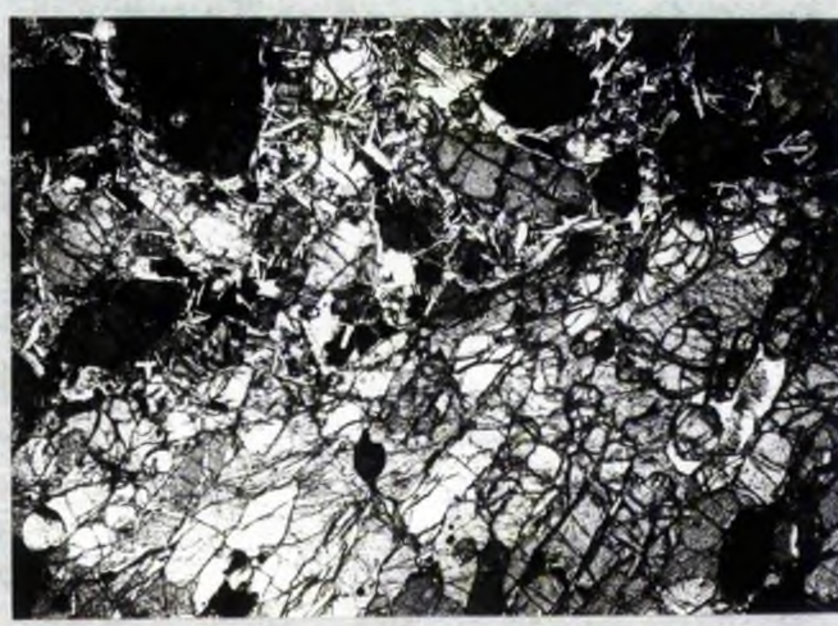

Fig. 91. Broken crystals of olivine and pyroxene at the contact of a xenolith with dyke rock. X 15; crossed nicols.

absence of any reaction between the xenoliths and their host rocks can be attributed mainly to the identical chemical compositions of the constituent minerals of both xenoliths and dykes. Since the xenoliths were incorporated in hot magma, some clouding of the plagioclase crystals might be expected (Poldervaart and Gilkey, 1954, p. 89). None, however, has been observed and, although this could be due to many factors, e.g. the calcic nature of the plagioclase (Poldervaart and Gilkey, 1954, p. 88), the most likely appears to be that the heating was not sufficiently prolonged.

The relationship between the xenoliths and their host rocks presents important evidence of the origin of the xenoliths and this is discussed in chapter XVIII.

4. DISTRIBUTION.

Field observations indicate that the distribution of cognate xenoliths is very irregular. The xenolith content varies considerably from dyke to dyke, between outcrops of the same dyke and even within a single outcrop. Where a dyke contains abundant xenoliths the xenoliths persist almost right to the edges of the dyke but appear to decrease in amount near the edges. In order to test this observation quantitatively the following method was devised and applied to dyke 1 (outcrop 1/2).

Large specimens collected at intervals across the dyke were cut along three mutually perpendicular planes, two of which were vertical and contained respectively the dip and strike of the dyke. The resulting faces were polished to make the xenoliths more conspicuous. Outlines of these faces and the xenoliths exposed therein were traced on to centimetre graph paper and the volumetric content of xenoliths determined. Small discrepancies occur between the results obtained from different faces of the same specimen but these are almost certainly due to the sampling error. They cannot be attributed to any preferred orientation of the xenoliths (see following section) which, according to Shaw and Harrison (1955), would not produce such discrepancies.

The average xenolith contents of four specimens from the thirty foot wide dyke 1 in outcrop 1/2 are given in Table 28. Four xenolith contents are insufficient for the preparation of a distribution curve similar to those given earlier for the minerals in several of the dykes, but the results appear to confirm the field observation that the xenolith content decreases towards the edges of the dyke.

TABLE 28

Xenolith contents of specimens from dyke 1
(outcrop 1/2)

Distance from S.W. Contact	% Cognate Xenoliths
0 ft. 5 ins.	17.2
4 ft. 10 ins.	26.3
7 ft. 6 ins.	25.2
30 ft. 0 ins.	1.2

Mainly from the field evidence therefore, it appears that :- (i) the distribution of cognate xenoliths is random with local concentrations and (ii) there is a tendency for the margins of the dykes to contain fewer xenoliths than the centres.

5. ORIENTATION.

On many of the weathered faces, particularly those sub-parallel to the margins of the dykes, there appears to be a tendency for elongate xenoliths to exhibit a parallelism (Fig. 92). The orientations of the long axes of the cross-sections of the xenoliths exposed on each of the

Fig. 92. Parallelism of elongate xenoliths in dyke 1 (outcrop 1/2).

three mutually perpendicular planes (see previous section) have been determined. The results for the corresponding planes from each specimen have been combined to produce the orientation diagrams presented in Fig. 93. Fig. 93a and b indicate that there is no strong preferred orientation of elongate xenoliths in either the horizontal plane or the vertical plane perpendicular to the strike of the dyke. Because of the relatively small sample the rose diagrams have several minor peaks which are of little significance. In the vertical plane parallel to the strike (Fig. 93c), however, there is a strong preferred orientation of the elongate xenoliths. Since no preferred orientation is visible in either of the planes perpendicular to this one it is evident that there is no planar orientation of the xenoliths, i.e.

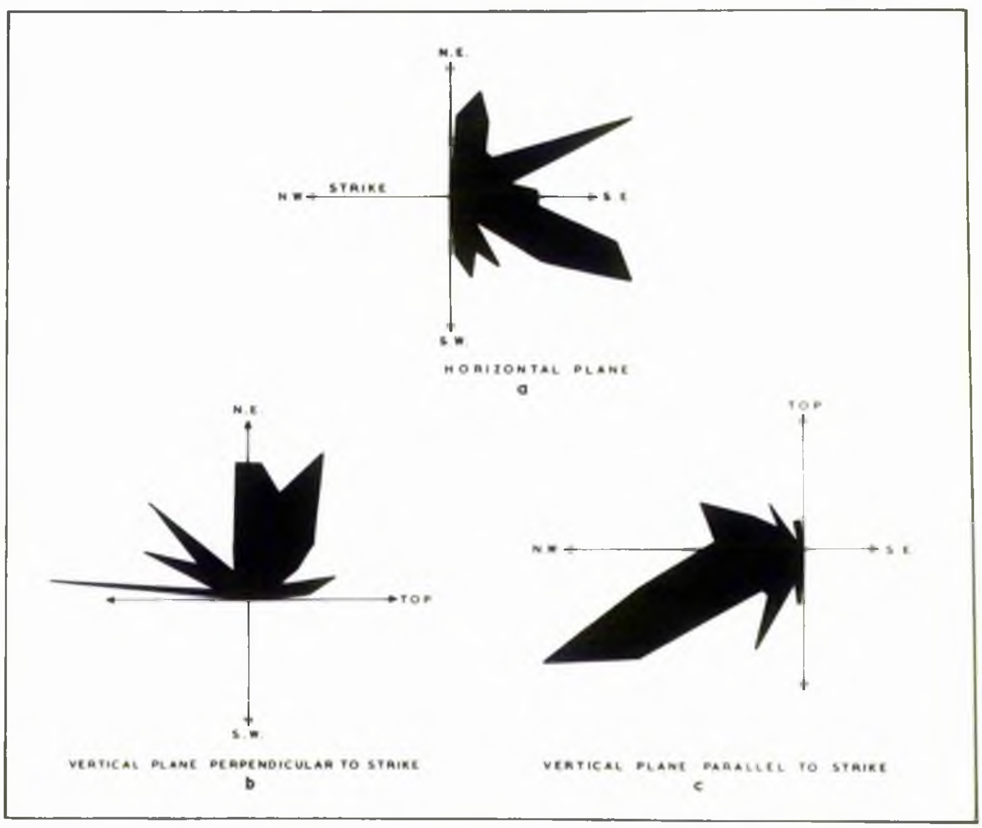

Fig. 93. Orientation diagrams, each for approximately 60 elongate xenoliths in dyke 1 (outcrop 1/2).

there is a linear orientation of the long axes of the xenoliths with the intermediate and short axes randomly orientated in the plane perpendicular to the long axes. The plane represented in Fig. 93c is almost parallel to the walls of the dyke [dyke 1 is not quite vertical] and it appears, therefore, that there is a preferred orientation of the long axes of the elongate xenoliths at an inclination of 20-30^{o} to the horizontal in the plane parallel to the walls of the dyke.

6. DISCUSSION.

A linear parallelism of prismatic or lath-shaped crystals in lavas is normally attributed to flow, with the parallelism corresponding to the direction of flow. Unfortunately, to the best of the writer's knowledge, the motions of tabular and irregularly shaped solid bodies in a flowing viscous medium have not been studied in detail, but it has been demonstrated theoretically (Jeffrey, 1923) and experimentally (Taylor, 1923) that, in a uniform shear flow (i.e. laminar flow), the long axis of an ellipsoid of revolution rotates in a plane perpendicular to the vortex lines. The rate of this rotation, however, is not constant and for most of the time the long axis is parallel to the stream lines (i.e. the direction of flow). If the extrapolation of these results to the xenoliths, which are not solids of revolution, is valid, a linear parallelism of the long axes of the type observed should have occurred during the intrusion of the dykes. It seems, therefore, that the preferred orientation of the long axes of the xenoliths is a flow structure and that the orientation is parallel to the direction of flow.

Theoretically, a similar linear orientation of elongate olivine crystals should occur. However, it would not be so well developed due to much greater mutual interference and it would be largely masked by the high proportion of sub-equant anhedral crystals. Detection of such an orientation by petrofabric analysis would be further complicated by the tendency for olivine crystals to be elongated parallel to both the a and c crystallographic axes.

The inclination of the horizontal of the long axes of the xenoliths and, therefore, of the direction of flow is particularly significant. It indicates that dyke 1 flowed both upwards and in a south-easterly direction. The former is consistent with a fundamental assumption accepted previously (chapter XI.3) and the latter is compatible with the hypotheses advanced in chapters XVI.2 and XVII.

It has already been demonstrated (chapter XI.3) that the axial migrations of olivine crystals in the dykes increased with the size of the crystals. Since the cognate xenoliths are much larger than the largest of the olivine crystals it appears that axial migration of the xenoliths should have been much greater than that of the olivine crystals. Consequently, the xenoliths should be concentrated in a very narrow axial zone. Although the extreme edges of the dykes contain fewer xenoliths than the rest of the dykes, it is evident that no extreme axial concentration of this type has occurred. However, before this lack of axial concentration of the xenoliths can be accepted as a valid objection to the mechanism of differentiation tentatively proposed in chapter XI.3, two factors must be considered.

Firstly, the densities of the xenoliths, other than those composed of dunite, are less than that of the olivine crystals and this may have had some effect on the axial migration. However, the differences in density are insignificant compared with the differences in size, and it appears unlikely that the lack of extreme axial migration of the xenoliths could have been due to this factor alone.

Secondly, for axial migration to take place, it is essential that the migrating body is able to rotate in, and move laterally through, the suspending medium. There is little doubt that the olivine crystals migrated through the suspending liquid, often until they became so concentrated that mutual interference prohibited any further movement. The xenoliths, however, would have had to move through a mush of olivine crystals, which was often more than 60% solid material, and movement of the xenoliths under such conditions appears highly improbable.

Since the elongate xenoliths evidently aligned their long axes parallel to the flow, some rotation must have been possible. However, the longitudinal forces which orientated these xenoliths would have been much stronger than the transverse forces tending to produce axial migration, and it does not follow that since the xenoliths rotated they should have migrated axially. Nevertheless, the impoverishment in xenoliths of the extreme margins of the dykes is evidence that slight axial migration did occur. It appears highly significant that this migration was confined to the parts of the dyke where the olivine concentration was lowest.

It may therefore be concluded that, despite the much greater size of the cognate xenoliths relative to the olivine crystals, the distribution of xenoliths was virtually unaffected by flowage differentiation because of the increase in viscosity imparted to the liquid by its content of olivine crystals. Consequently, the distribution of xenoliths is not incompatible with the differentiation hypothesis.

XIII BANDING.

1. MARGINAL LAMINATION.

The margins of many of the dykes (Table 5) exhibit a prominent lamination parallel to the contacts which is related to a fissility of the rock (Fig. 94). Probably the best development of this lamination

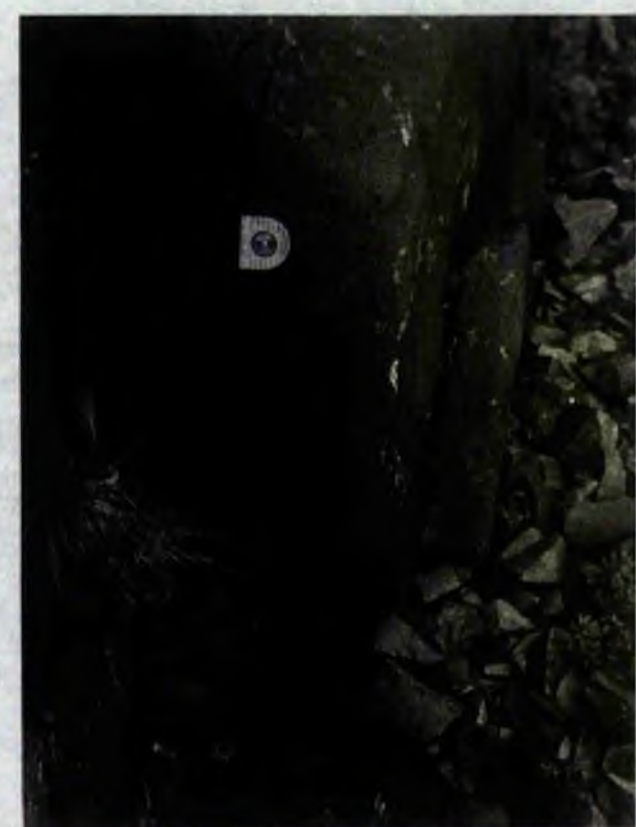

Fig. 94. Lamination near the south-west edge of dyke 6.

is at the south edge of dyke 28 in outcrop 28/2. Although the actual contact is not exposed, field and petrographical evidence indicates that the exposed south edge of the dyke is relatively close to the contact. This is undoubtedly the example described by Bowen (1928, p. 156) and Phillips (1938, p. 132-133). The rocks from this dyke studied by both Bowen and Phillips were dunites. Bowen concluded that the lamination was due to "a parallel arrangement of elongated blades of olivine" and Phillips prepared petrofabric diagrams for the dunite and observed that "there is a definite elongation of many of the olivine crystals parallel to the plane of fissility".

As mentioned in the preceding chapter, a slight linear parallelism of the olivine crystals might have arisen during flow, but a strong planar parallelism of the type recorded by Bowen and Phillips would have been unlikely to arise during flow. Consequently, the marginal lamination, especially that of dyke 28, has been carefully re-examined. The marginal rock of dyke 28 is not dunite but picrite. Xenoliths of dunite and felspathic peridotite are abundant at the edge of dyke 28 in outcrop 28/2, and many of them are more than a foot long.

The fissility is due to innumerable tiny fractures in the olivine crystals. These fractures are sub-parallel to the edges of the dykes but there is no particular orientation of elongate olivine crystals parallel to the fissility, and fractures perpendicular to the elongation direction of individual crystals are common (Fig. 95).

Fig. 95. Minute fractures in olivine crystals from dyke 28; X 15, plane polarized light.

The fissility passes through the xenoliths and, since the fractures are only prominent in olivine crystals, it is best developed in xenoliths of dunite and olivine-rich felspathic peridotite. In many of the dunite xenoliths there is a very well developed planar parallelism of elongate and tabular olivine crystals but there is no preferred orientation of this plane parallel to the fissility and the two are often almost at right angles (Fig. 96).

It appears probable that the specimens from dyke 28 examined by both Bowen and Phillips were selected because they exhibited a

Fig. 96. Fissility sub-perpendicular to the direction of elongation of olivine crystals in a dunite xenolith from dyke 9; X 15; crossed nicols.

particularly good laminar structure and that consequently, both were in fact dunite xenoliths: in the case of the one studied by Phillips the correspondence between the planar orientation of the olivine crystals and the fissility must have been coincidental.

Antigorite and secondary magnetite are generally developed, sometimes extensively, along the minute fractures and it is the differential weathering of these secondary minerals which has given rise to the lamination, the fractures along which the alteration is most extensive appearing on the weathered surface as planes of parting in the rock. Incipient fractures occasionally occur in the crystals of pyroxene and plagioclase. The most likely cause of the fracturing is contraction when the dykes cooled. The laminar structure persists right across a few of the dykes and in such cases the fractures are slightly wider apart in the centres of the dykes than at their margins.

2. THIN BANDING.

a). Sub-horizontal Banding.

A thin sub-horizontal banding occurs locally in a few of the dykes but is extensively developed only in dyke 9. This banding produces a rippled effect on vertical and near vertical weathered surfaces due to differential weathering of alternating bands of slightly different compositions. Individual bands are generally between one and six inches thick and may occur singly (Fig. 97) or in succession (Fig. 98). Even where they are abundant these bands show lateral impersistence (Fig. 99) and nowhere have they been observed close to the contact of a dyke.

Fig. 97. Thin sub-horizontal band in dyke 9 (outcrop 9/4).

Fig. 98. Sub-horizontal banding in dyke 9 (outcrop 9/3).
[Note pod-shaped pits (see chapter V.1.a)].

If the more resistant bands forming the crests of the ripples are traced until they occur on a relatively flat surface (Fig. 99 and left end of Fig. 97) it can be seen that they are composed of a rock which does not give rise to such a pitted surface on weathering as the less resistant bands forming the troughs. Since the pits are produced by the weathering out of large olivine crystals it appears that adjacent bands differ in their content of such crystals.

Examination of the bands in thin section confirms that the main difference between adjacent bands is that the olivine crystals in the more resistant bands are slightly smaller than those in the others. In addition, the more resistant bands generally contain slightly less

Fig. 99. Impersistent sub-horizontal bands in dyke 9.

olivine than the adjacent rock: for example the band shown in Fig. 97 contains 50% olivine compared with 59% in the rock immediately above the band. The junctions between the bands appear to be sharp and no evidence of any gradation within the bands has been observed.

It is evident that the bands must have been formed after flow ceased otherwise they would have been disrupted by flowage differentiation. The banding is similar in appearance to the rhythmic layering in the ultrabasic rocks of Rhum illustrated by Wadsworth (1961, fig. 6). According to Wadsworth (1961, p. 60-62), the rhythmic layering is due to periodic nucleation of crystals which sank in the magma. It has already been shown that almost all the olivine crystals were present in the magma before the dykes were emplaced and therefore, the banding in the dykes cannot be attributed to a similar process.

The writer can at present offer no satisfactory explanation of this phenomenon, but it appears from the impersistent nature of the banding and the shapes of some of the bands (Fig. 100) that some

Fig. 100. Impersistent sub-horizontal bands in dyke 9 (outcrop 9/4).

form of local mechanical mixing of two layers of magma containing slightly different amounts of large olivine crystals may have occurred.

Since the olivine content and the size of the olivine crystals increase from the edges of the dyke towards the centre, it is obvious that such layers of magma were readily available. If mixing occurred it must have done so in the interval between the cessation of flow and the crystallization of the groundmass minerals since the plagioclase and pyroxene are identical throughout the banding. Local swirling of the already differentiated suspension after flow ceased does not seem unlikely in the dykes but such a mechanism would not account for the sub-horizontal disposition of the bands and cannot therefore be regarded as a satisfactory explanation of the observed phenomenon.

b). Vertical Banding.

A faint planar structure parallel to the contacts of dyke 8 has been observed in one outcrop (8/1). It occurs at the south-west edge of the dyke and is visible only within one foot of the contact. Like the sub-horizontal banding described above, it produces a rippled surface on weathering but the ripples are less prominent (Fig. 101). However, unlike the sub-horizontal banding, the vertical banding is not due to a variation in the olivine contents of adjacent bands, but appears to be caused by slight changes in the plagioclase:pyroxene ratio, the more felspathic bands being more resistant to erosion than the more pyroxenic bands. The vertical banding therefore appears to be due to minor fluctuations in the crystallization conditions of the dyke margins as cooling progressed inwards from the contact. Since only one isolated instance has been recorded, and it is evidently a minor feature of the dykes, no further attempt is made to account for the vertical banding.

Fig. 101. Vertical banding at the south-west edge of dyke 8.

3. GRADATIONAL BANDING.

Only two examples of this type of banding have been observed. Both occur in dyke 1 (outcrop 1/2) within a few feet of the north-east contact of the dyke. The lower example is just above the locality illustrated in Fig. 18. A sharp change in grain-size is visible on a vertical weathered surface sub-parallel to the contact (Fig. 102).

Fig. 102. Top of a gradational band in dyke 1.

Below the level of this change the small pits produced by the weathering out of olivine crystals are abundant but above it they appear to be relatively rare.

The second example occurs approximately 20 feet above the first, again on a vertical face sub-parallel to the contact. Where this face emerges from the grass (Fig. 103) the surface is relatively poor in pits but they gradually become more numerous in an upward direction until 19½ inches above the lowest point of the exposure there is a sudden reversion to a surface on which pits are relatively rare. Above this the pits again increase gradually in number, attaining a maximum about 25 inches above the sudden change. Above the maximum there is a gradual decrease in the number of pits until 28½ inches above the level of the

Fig. 103. Gradational banding in dyke 1.

sudden change there is a second sudden return to a surface on which there are relatively few pits. Above the second abrupt change the upward increase in the number of pits is not so evident.

Examination of thin sections from the second example confirms that the variations in the number of pits are due to a differential distribution of large olivine crystals. The olivine contents of six specimens, four of which are from the complete middle band, have been determined and an approximate olivine distribution curve for part of the face shown in Fig. 103 has been prepared (Fig. 104).

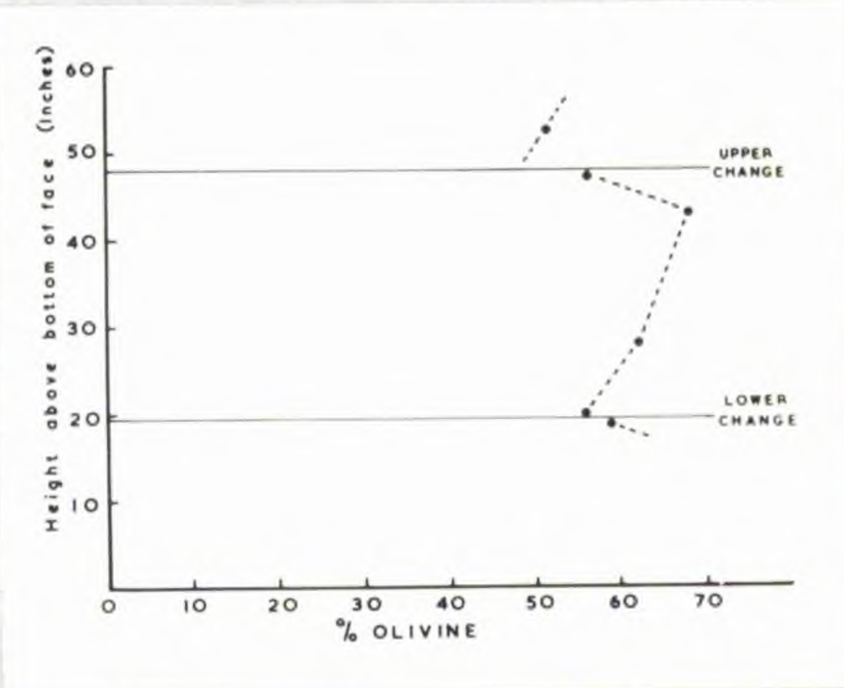

Fig. 104. Distribution of olivine in a vertical section through part of the face illustrated in Fig. 103.

It is evident from the above descriptions and Figs. 102, 103 and 104 that the size and amount of the olivine crystals increase gradually towards the top of each band, although they may decrease immediately below the top. Consequently, this type of banding is referred to as gradational banding. Both the quantitative and size gradations are the opposites of those which would arise from gravitative settling of olivine crystals of assorted sizes (cf. Irvine, 1963, p. 39). The writer is unable to offer a satisfactory explanation of this type of banding but considers it possible that a mechanism similar to that tentatively suggested for the sub-horizontal thin banding could produce gradational banding. The larger scale of the gradational bands may have permitted some form of differentiation within the bands. It is, however, difficult to account for the fact that the olivine crystals are concentrated near the tops of the bands. Whatever the origin of the gradational banding it is undoubtedly a secondary differentiation and does not appear to have occurred on a scale sufficiently widespread to have obscured the primary flowage differentiation pattern.

4. LAYERING.

In dykes 12 and 14 a type of layering* is locally developed. This layering is sub-horizontal and occurs in the central parts of both dykes. It is due principally to variations in the size of the large crystals of plagioclase and (to a lesser extent) pyroxene which poikilitically enclose the olivine crystals.

Layering is particularly well-developed on a vertical face at the east end of outcrop 14/5 (Fig. 105). At the base of this face the plagioclase crystals are frequently more than 2 cm. long and the weathered surface is exceptionally rough. Approximately 5 feet from the bottom of the face the size of the felspars decreases slightly and weathering produces a smoother surface on which a faint, impersistent banding, not unlike that described in section 2.a of this chapter, is visible. About 13 feet above the bottom of the face the felspars begin to increase in size and, over the topmost few feet, the weathered surface becomes noticeably rougher. Even at the very top of the face, however, the surface is not as rough as at the bottom.

*The term layering is used simply to denote a planar structure on a slightly larger scale than the observed banding effects and does not imply the existence of any cryptic chemical variations within the layers.

Fig. 105. Layering in dyke 14.

A few yards to the west of the above face is a 26 foot high vertical face in which layering of this type is again present (Fig. 106). The field relations suggest that the bottom of this face is at approximately the same level in the intrusion as the top of the first and, since the two faces appear to be identical, it seems reasonable to assume that the

Fig. 106. Layering in dyke 14.

base of the second face is a lateral extension of the top of the first. The size of the plagioclase crystals and the roughness of the weathered surface gradually increase towards the top of this second face until a few feet from the top of the face the rock is as coarse-grained as that at the bottom of the first face. One foot from the top of the second face the very coarse-grained rock gives way abruptly to a much finer-grained variety in which thin sub-horizontal banding is prominently developed (Fig. 106, top left). In this rock the plagioclase crystals are less than 4 mm long compared with more than 2 cm long below the abrupt change.

If the above interpretation of the relationship between the two faces is correct, it appears that one complete layer is of the order of 35 feet thick and grades upwards from a medium-grained rock, in which sub-horizontal thin banding may occur, to a very coarse-grained variety. The junctions between layers seem relatively sharp. The layering in dyke 12 is not so prominent and a complete layer has not been observed.

It is evident that the variations in the sizes of the plagioclase and pyroxene crystals, and consequently, the layering, were caused by changes in the conditions under which these minerals crystallized. However, the mechanisms by which these conditions were varied are much less evident and two possible processes are tentatively suggested below.

If tranquil conditions favoured growth of a few large crystals and more turbulent conditions favoured growth of many small crystals, the layering could be attributed to pulsations within the crystallizing magma. Each sudden change to a finer-grained rock would correspond to a sudden movement of the magma and the remainder of the layer to a gradual return to quiescence. During the return to tranquil conditions, the size of the crystals nucleating from the magma would gradually increase and eventually there would be a reversion to the nucleation of very large crystals which would prevail until the next movement within the magma. The presence of thin sub-horizontal banding immediately above the sudden change to finer-grained rock is compatible with this hypothesis. There are, however, two important objections to this mechanism: firstly, there is little evidence that increased tranquility decreases the rate of nucleation of crystals from magma, and secondly, it appears improbable that the after-effects of a single pulsation would last sufficiently long to permit the crystallization of the observed thickness of rock between the base of the layer and the reappearance of the coarsest-grained variety.

The alternative possibility is that the degree of supercooling of the magma, and hence the rate of crystal nucleation, fluctuated. This might have been effected by a cyclic process involving gradual build-up of the vapour pressure of the volatile phases followed by sudden release of pressure in a manner similar to that suggested by Kushiro (1964, p. 198-199).

In the writer's opinion the first process appears less likely than the second. However, neither of these mechanisms can account for the sub-horizontal disposition of the layering unless the cooling surface of the dyke was also sub-horizontal and all the other evidence concerning the cooling of the dykes indicates that this was not the case.

XIV. OFFSHOOTS AND VEINS.

1. OFFSHOOTS.

Small offshoots from the dykes occasionally penetrate the country rock for a short distance and six of these are briefly described below.

Just above the lower end of outcrop 18/2 an offshoot emerges from the south edge of the dyke. Where it leaves the dyke it is 3 inches wide, and it narrows continuously along its length until it dies out 3 feet from its source. Near the lower end of outcrop 18/3 another offshoot from the south edge of dyke 18 cuts the country rock. This offshoot is 2 inches wide where it leaves the dyke, and narrows away from the dyke, pinching out within 18 inches of its source. Both offshoots are composed of a crypto-crystalline groundmass containing minute, acicular plagioclase crystals and occasional small, subhedral olivine crystals or antigorite pseudomorphs after olivine. The groundmass appears to be formed mainly of pyroxene. The offshoots are chilled against the country rock and the degree of chilling appears to increase away from the dyke (cf. Figs. 107 and 108).

A similar offshoot from the north edge of dyke 29 in outcrop 29/1 is 4 feet long and is 8 inches wide at its junction with the dyke. Petrographically it is almost identical with the two offshoots described above but, since it is thicker, the acicular plagioclase crystals in the centre of

Fig. 107. Offshoot from dyke 18 chilled against gabbro 1 inch from the dyke. X 12; plane polarized light.

Fig. 108. Offshoot from dyke 18 chilled against gabbro 18 inches from the dyke. X 12; plane polarized light.

the offshoot are slightly larger and the groundmass is composed dominantly of recognisable pyroxene crystals. This offshoot has a sub-ophitic texture and its margins are chilled against the country rock. The chilling is more intense than that of the offshoots from dyke 18 and this is undoubtedly related to the fact that the edges of dyke 29 cooled more rapidly than those of dyke 18 (Table 4).

A few feet from the north edge of dyke 10 in outcrop 10/1 two stringers of ultrabasic rock cut the gabbro. Both are between 2 and 3 inches thick and pinch out at either end, i.e. they are not visibly connected to the dyke, but there seems to be little doubt that these stringers are offshoots of dyke 10. [One is shown in Fig. 109.]

Fig. 109. Offshoot from dyke 10.

They are composed of abundant subhedral olivine crystals up to 4 mm long and a few small chrome spinels in a partially devitrified hyaline groundmass and are, therefore, identical with the matrix of the contact breccia of dyke 10 (chapter V.2.j).

An offshoot from the west side of dyke 31 in outcrop 31/3 is two or three inches thick at its source but is truncated within a few inches by the edge of the outcrop. This offshoot is composed of subhedral olivines less than 2 mm long in a sub-ophitic intergrowth of pyroxene and plagioclase crystals often more than 1 mm long. It is not chilled against the gabbro and does not become finer-grained at the edges. This evidence suggests that dyke 31 did not have chilled edges, thus implying that the country rock must have been hot when the dyke was emplaced (see chapter V.1.c).

Bowen (1928, p. 158) quite rightly placed considerable significance on the nature of these offshoots, but he interpreted them, incorrectly, as indicating the existence of a basaltic magma (chapter XI. 1). The offshoots merely reflect the nature of the material which flowed along the extreme edges of the dykes and which was generally impoverished in olivine crystals by flowage differentiation. The very narrow offshoots into which such olivine crystals as were present in the dyke margins could not be transported, however, reflect only the nature of the suspending fluid.

2. POST INTRUSIVE VEINS.

a) Pegmatitic Veins.

Coarse-grained gabbroic veins have been observed in dykes 12 and 14. They are generally about two inches wide and seldom extend for more than two feet. One such vein in dyke 14 (Fig. 110) appears to be continuous with the country rock but otherwise these veins run entirely within the dykes. Although they occur predominantly in the marginal parts of the dykes they have been observed more than five feet from the contact. The veins are not chilled against the dyke rock but a thin rusty weathering zone occurs at the junction between the two.

The veins are formed mainly of pale brown clinopyroxene and plagioclase with subordinate amounts of olivine, magnetite and ilmenite.

Fig. 110. Pegmatitic veins at the north-east edge of dyke 14 (outcrop 14/5).

The plagioclase crystals, which may be as long as 5 mm, are generally clouded. The larger plagioclase crystals are sub-ophitically intergrown with the pyroxene but the smaller ones are ophitically enclosed (Fig. 111). The crystals of magnetite and ilmenite are mostly skeletal.

Fig. 111. Pegmatitic vein. X 15; crossed nicols.

These pegmatitic veins may be due to back-veining by the country rock but no evidence of fusion of the gabbro by the dykes has been observed. In addition, these veins may transgress both dyke and gabbro. Similar pegmatitic gabbroic veins occur throughout the Cuillin gabbros and, consequently, the pegmatitic post-intrusive veins may have no genetic connection with the dykes.

b) Leucocratic Veins.

Occasional leucocratic veins about half an inch thick cut the dykes (Fig. 112). These may continue for several yards with no

Fig. 112. Leucocratic vein in a large specimen from dyke 1. X $\frac{1}{4}$.

significant change in width. They consist of a central zone, along which the dyke rock is extensively altered to secondary minerals, bordered by two marginal zones in which alteration is less intense. The central zone is composed of a fine aggregate of antigorite, chlorite, zeolites, zoisite and magnetite with relics of primary pyroxene and plagioclase. The magnetite crystals are commonly skeletal. The marginal zones are basically similar to the dyke rock, but much of the plagioclase is replaced by chlorite and the olivine crystals are pseudomorphed by antigorite.

Since these veins appear to be channels along which agents of deuteric alteration passed they probably correspond to a period of late-magmatic activity.

c) Thin "Red" Veins.

This is the commonest type of vein occurring in the dykes. They are generally less than $\frac{1}{8}$ of an inch thick and occupy the transverse joints which divide the outcrops into blocks (chapter V.1.a). They weather to a reddish brown colour but on a freshly exposed surface they are greenish white. They are very similar to the leucocratic veins, being composed of central and marginal zones of more and less intensely altered dyke rock. The central zone is formed mainly of antigorite, chlorite, magnetite, sericite and fibrous aggregates of tremolitic amphibole. This zone is usually less than 1 mm wide. The marginal zones are similar to those of the leucocratic veins.

Apart from their smaller size and appearance on a weathered surface, the thin "red" veins differ from the leucocratic veins only in their relationship to the transverse joints. It appears probable that the two types of vein were formed in a similar manner but, since migration of the agents of alteration was probably more rapid along the joints than elsewhere, the lateral extent of the alteration in the thin "red" veins was much less than in the case of the leucocratic veins.

XV. CRYSTALLIZATION OF THE DYKES.

The textural evidence indicates that in all the dykes the primary minerals crystallized in the sequence olivine - plagioclase - pyroxene, with spinel crystallizing before or along with the olivine. The pyroxene and most of the plagioclase evidently crystallised together after flow had ceased. However, there is no indication that any olivine crystallized contemporaneously with these minerals and, in fact, the almost complete absence of olivine crystals from the extreme margins of some of the dykes suggests that all the olivine had already crystallized when flow ceased.

The simple mineralogy of the dykes permits a valid comparison to be made with the experimentally investigated system diopside-forsterite-anorthite (Osborn and Tait, 1952). The average compositions of the dykes fall well within the forsterite field of this system and the experimental evidence supports the general crystallization sequence suggested by the textural evidence. According to the experimental evidence, however, a small amount of olivine should have crystallized along with the bulk of the pyroxene and plagioclase.

It has already been established (chapter XI.2) that the dykes were emplaced as suspensions of olivine crystals which were present in the magma before the intrusion of the dykes. It has also been suggested (chapter XI. 3) that, in at least one of the dykes, some of the plagioclase began to crystallize before flow ceased.

The accumulated evidence suggests, therefore, that the crystallization of the pyroxene, almost all of the plagioclase and (despite the lack of textural evidence) a little of the olivine, occurred *in situ.* In the extreme margins of some of the dykes the small "groundmass" olivines and the rare microphenocrysts present may represent the small amount of olivine which crystallized after flow had ceased, but it is more than probable that most of the olivine crystallizing from the liquid would have been deposited on the surfaces of the phenocrysts already present in the dykes.

The temperature and pressure conditions under which the dykes crystallized cannot be determined exactly but reasonable estimates can be made. It seems beyond doubt that the dykes were intruded below the same lava pile as the Cuillin plutonic complex. According to Anderson and Dunham (1966, p. 79) the entire volcanic series of Skye need not have been thicker than 4,000 feet. If this figure is accepted, the dykes must have been emplaced under load pressures of less than 500 bars (Turner and Verhoogen, 1960, p. 458).

It is evident from the minerals which crystallized after flow ceased (above) that the crystallisation of the dykes *in situ* commenced slightly above the eutectic temperature for the three principal minerals. At atmospheric pressure the eutectic temperature in the experimental system diopside-forsterite-anorthite is 1270^{o}C (Osborn and Tait, 1952). However, since there are fewer components in the experimentally investigated system than in the dykes, it seems likely that the eutectic temperature in the dykes would have been lower. In addition, the fact that the dykes cooled under pressure and the presence of volatile phases would have tended to lower this temperature further. The silicate liquidus temperatures of the selected basalts investigated experimentally by Yoder and Tilley (1962, fig. 7) vary between 1160°C and 1240°C and these basalts were completely crystallized less than 200°C below their liquidus temperatures. Recorded extrusion temperatures of basalt lavas are consistent with the experimental results (see Yoder and Tilley, 1962, p. 385) although lavas may remain mobile well below the experimentally determined temperature of complete crystallization due to the lack of equilibrium conditions in flowing lava. Since the dykes are more basic than basalts it appears reasonable to assume that they would have a higher liquidus temperature and would also be completely crystallized at a higher temperature than basalts. It therefore appears unlikely that the crystallization of the dykes *in situ* could have commenced below 1100°C and an estimate of 1150°-1200° appears reasonable.

It is evident from the different grain-sizes and textural relationships that the rate of crystallization varied within individual dykes as well as from one dyke to another. In the centre of many of the dykes the pyroxene and plagioclase crystals are very large, thus implying that the centres cooled relatively slowly whereas the finer grain-size of the margins suggests that they crystallized more rapidly. The centres of many of the dykes are identical with the corresponding plutonic rocks (e.g. those of the Sgurr Dubh intrusion) and it seems reasonable to assume that they crystallized under similar conditions. Consequently, it appears that the central parts of many of the dykes crystallized more slowly than is normal for dykes of a comparable size. In addition, it has already been suggested that the temperature differences between many of the dykes and their host rocks may not have been sufficient to produce chilled selvedges, and this may also have been responsible for the relatively slow cooling. Whether the relatively small temperature difference was due to substantial heating of the country rock by the dyke magma during prolonged intrusion or to the country rock being at an elevated temperature prior to the intrusion of the dykes, is uncertain, but, in the writer's opinion, the former is less probable than the latter (see also chapter V.1.b).

Sub-variolitic texture occurs in a few of the dykes (Table 7). To the best of the writer's knowledge, no satisfactory explanation of variolitic and sub-variolitic textures has even been given but it appears from their petrological occurrences that they are associated with very rapid cooling and consequently, with rapid crystallization e.g. in pillow lavas (Bailey et al., 1924, p. 24-25, p. 150) and in variolite dykes (Anderson and Dunham, 1966, p. 152-153). The most notable instance of sub-variolitic texture in the dykes is in the centre of dyke 10 and it is evident from its chilled selvedges and contact breccia that this dyke cooled more rapidly than most of the dykes. Between the chilled selvedges and the sub-variolitic centre of this dyke, however, the margins exhibit a sub-ophitic texture and, if sub-variolitic texture is to be invariably attributed to more rapid cooling than sub-ophitic texture , the centre must be regarded as having cooled more rapidly than the margins. However, since the loss of heat from the dykes was outwards, this appears most unlikely.

Rapid crystallization, however, need not be due to rapid cooling and Oppenheim (1964, p. 554) has suggested that "an unusually high distribution of phenocrysts.......... could promote a rapid crystallization". The centre of dyke 10 contains more than 70% olivine crystals and the margins very much less than this, so that, according to Oppenheim, crystallization could have been more rapid in the centre than in any other part of the dykes except the chilled selvedges. It may be significant, in the light of Oppenheim's suggestion, that approximately coincident with the junctions between the olivine-rich and non-porphyritic parts of both sill 2 on Soay (Drever and Johnston, 1958, p. 478) and sheet 26 (chapter XX) there is a change from variolitic/ sub-variolitic texture to sub-ophitic texture.

The above hypothesis must be regarded as extremely tentative but, whatever the origin of variolitic and sub-variolitic textures, it appears that they are results of abnormal crystallization conditions.

XVI RELATIVE AGE OF THE DYKES.

1. INTRUSIVE SEQUENCE OF THE CUILLIN IGNEOUS COMPLEX.

It has already been demonstrated (chapter V.1. c) that the dykes are not the youngest igneous rocks in the area, as Harker suggested, and the problem of their relative age is re-examined below. Before discussing the age of the dykes, however, it is necessary to review the intrusive sequence of the Cuillin igneous complex. For the purpose of this chapter it is sufficient to consider the intrusions forming the basic/ultrabasic complex, and the epigranites, etc. (Wager et al., 1965) forming the Red Hills complex to the north-east may be omitted.

The Cuillins were first geologically surveyed in detail by Harker (1904) who proposed the following sequence of volcanic, plutonic and hypabyssal rocks :-

Youngest

Radial set of ultrabasic dykes
Inclined basic sheets
Radial set of basic dykes
Tangential set of basic dykes
Gabbro "laccolite"
Sgurr Dubh ultrabasic "laccolite" and "feeder dykes".
Basalt lavas

Oldest

Weedon (1961) re-mapped the southern part of the Cuillins and sub-divided the gabbro. He suggested that the gabbros on the convex southern side of the Sgurr Dubh intrusion were older than the ultrabasic rocks and proposed the following revised sequence of plutonic intrusions :-

Youngest		
	Inner Layered Gabbro	
	Sgurr Dubh ultrabasic intrusion	
	Ghrunnda and Ring Eucrites	Outer Gabbro
	Gars-bheinn and Clouded Felspar Gabbros	Outer Gabbro
Oldest		

The writer (Gibb, 1965) also suggested that the age relationship between the Sgurr Dubh ultrabasic intrusion and the Cuillin gabbros proposed by Harker was wrong.

Hutchison (1964) recently remapped the western part of the Cuillins and has kindly discussed his results with the writer in a series of personal communications. He observed that the Ring Eucrite is altered against the Gars-bheinn Gabbro and, on this basis suggested that the units composing the Outer Gabbro were emplaced in the order; Ring Eucrite - Gars-bheinn Gabbro - Ghrunnda Eucrite, with the Clouded Felspar Gabbro being formed of altered rocks from all three units. [For the distribution of these units see Weedon (1961, fig. 1).] In the western Cuillins Hutchison found that the Ring Eucrite continues as the outermost member of the plutonic complex and that within it, and chilled against its inner margin, is a large intrusion of Layered Allivalites of which the Ghrunnda Eucrite is a marginal facies. Two tholeiitic complexes are present in the western Cuillins. One of these follows the main ridge of the Cuillins, intruding mainly the Layered Allivalites, and is referred to as the Main Ridge Tholeiitic Complex. The other, the Outer Tholeiitic Complex, occurs near the periphery of the Cuillins and intrudes the Ring Eucrite. Hutchison correlated the Outer Tholeiitic Complex with the Gars-bheinn Gabbro since they are petrographically and chemically similar and the Ring Eucrite is similarly altered in the vicinity of both.

From the evidence presented by the above writers, therefore, it appears that the major intrusions forming the western and southern parts of the Cuillins were emplaced in the following sequence :-

	Western Cuillins.	Southern Cuillins
Youngest		
	Main Ridge Tholeiitic Complex	
		Inner Layered Gabbro
		Sgurr Dubh ultrabasic intrusion
	Layered Allivalites	Ghrunnda Eucrite
	Outer Tholeiitic Complex	Gars-bheinn Gabbro
	Ring Eucrite	Ring Eucrite
Oldest		

According to Harker there were four groups of minor intrusions, all of which were emplaced after the plutonic intrusions. However, at least seven groups of dykes and sheets, including two groups of tangential dykes, can be distinguished and there is evidence that the older group of tangential dykes is earlier than some of the major intrusions. In the lower part of Coir' a' Ghrunnda the Gars-bheinn Gabbro (which, in this area, contains clouded felspar) is cut by numerous basic dykes of the older tangential group. Higher up the corrie, however, these dykes have not been observed cutting the Ghrunnda Eucrite and they also appear to be absent from the Sgurr Dubh ultrabasic intrusion. Although this is negative evidence, it implies that these dykes were intruded before the emplacement of the Ghrunnda Eucrite. The relative ages of the various groups of minor intrusions can be determined from their cross-cutting relationships and are given at the end of the following section.

2. POSITION OF THE DYKES IN THE INTRUSIVE SEQUENCE.

One of the most important factors in attempting to determine the position of the xenolithic ultrabasic dykes in the intrusive sequence is undoubtedly their distribution. To the best of the writer's knowledge they occur only on the convex side of the Sgurr Dubh intrusion. They have been observed intruding the basaltic lavas, the Ring Eucrite, the Gars-bheinn Gabbro (including the Clouded Felspar Gabbro), the Outer Tholeiitic Complex, the Layered Allivalites and the Ghrunnda Eucrite but appear to be absent from the Sgurr Dubh ultrabasic rocks and the Inner Layered Gabbro.

The dykes are cut by the majority of the minor intrusions which they intersect but are later than a few basic dykes (chapter V.1.c). In Coir' a' Ghrunnda and on An Diallaid these basic dykes can be seen to belong to the older tangential group, and it is probable that the other basic dykes cut by the xenolithic ultrabasic dykes also belong to this group.

It therefore appears that the ultrabasic dykes of the Ben Cleat type are later than the Ghrunnda Eucrite but were emplaced before, or simultaneously with, the Sgurr Dubh intrusion. They are later than the older tangential basic dykes but earlier than all the other minor intrusions.

The dykes are similar to the rocks of the Sgurr Dubh intrusion in many respects. It was demonstrated in chapter VII that, mineralogically, the dykes are identical with the lower part of this intrusion. Like the dykes, the Sgurr Dubh intrusion contains cognate xenoliths and these xenoliths can be matched type for type with those in the dykes. A few ultrabasic dykes were considered by Harker to be feeders of the Sgurr Dubh intrusion and, as Drever and Johnston (1958, p. 464) observed, there is no apparent difference between these and the dykes he referred to as "later peridotites". These factors, together with the apparent radiation of the dykes (except dyke 10) from the Sgurr Dubh intrusion, suggest that the dykes are related to this intrusion. None of the dykes, with the possible exception of dyke 10 (see below), exhibit any field relations disproving emplacement contemporaneously with the Sgurr Dubh intrusion. There is, therefore, no evidence that Harker's "early" and "late peridotite" dykes do not belong to the same suite and that this suite is not genetically associated with the Sgurr Dubh intrusion. Harker also assigned the "picrite boss of An Sguman" to the period of "later peridotites" and it seems probable that this mass of ultrabasic rock, intruded between the Ring Eucrite and the lavas on the southern edge of the Cuillins, belongs to the same period of igneous activity as the dykes and the Sgurr Dubh intrusion.

The ultrabasic dykes of the Coire Lagan type are evidently much later than the dykes of the Ben Cleat type. They are abundant in both the Sgurr Dubh rocks and the Inner Layered Gabbro and cut all the minor intrusions which they intersect except a few very late lime-rich aphanitic dykes (chapter V.l.c; Drever and Johnston, 1958, p. 471).

The following order of emplacement of the major and minor intrusions is tentatively proposed :-

<u>Youngest</u>

Lime rich aphanitic dykes
Ultrabasic dykes (Coire Lagan type)
Inclined basic sheets
Radial basic dykes
Tangential basic dykes (younger group)
Main Ridge Tholeiitic Complex
Inner Layered Gabbro
Sgurr Dubh and An Sguman ultrabasic intrusions and <u>ultrabasic dykes (Ben Cleat type)</u>
Layered Allivalites and Ghrunnda Eucrite
Tangential basic dykes (older group)
Gars-bheinn Gabbro and Outer Tholeiitic Complex
Ring Eucrite
Basalt Lavas

<u>Oldest</u>

[There are undoubtedly more groups of minor intrusions than those listed above but no attempt has been made to discriminate between them].

Dyke 10, which was tentatively classified as the Ben Cleat type (chapter IV) occurs on the main Cuillin ridge. It intrudes medium-grained gabbro which may be part of the Main Ridge Tholeiitic Complex. If this is the case, either the proposed age relationship is wrong or dyke 10 is not of the Ben Cleat type. It was observed previously (chapter IV) that dyke 10 exhibits many of the properties of the Coire Lagan type of ultrabasic dyke and it is the only one of the dykes classified as the Ben Cleat type which does not appear to radiate from the Sgurr Dubh intrusion. If the dyke does, in fact, cut the Main Ridge Tholeiitic Complex the balance of evidence is altered and dyke 10 ought to be tentatively classified along with the dykes of the Coire Lagan type.

It is concluded, therefore, that the ultrabasic dykes of the Ben Cleat type are significantly older than was previously suggested (Harker, 1904) and that their position in the intrusive sequence of the Cuillin Tertiary igneous complex is that shown in the order of emplacement tentatively proposed above.

XVII ORIGIN OF THE DYKES

It has already been demonstrated (chapter XI.2) that the dykes were intruded as suspensions of olivine crystals and, consequently, any attempt to establish the origin of the dykes is essentially an attempt to determine the source of these suspensions. Since the writer believes the dykes to be genetically connected with the Sgurr Dubh intrusion the origins of both are considered together.

There appear to be three possible ways in which the Sgurr Dubh intrusion could have been formed and these are considered below.

Hutchison, following Zinovieff (1957), suggested that the Sgurr Dubh rocks belonged to the same fractionation series as the Layered Allivalites. He proposed that the Sgurr Dubh rocks may represent the basal accumulate from the magma which formed the Layered Allivalites (which according to Zinovieff, are approximately 6000 feet thick). The accumulation was followed by emplacement of the Sgurr Dubh rocks into their present position by subsequent uplift. It appears highly improbable to the writer that the intercumulus liquid of the basal accumulate would not have crystallized during the crystallization of several thousand feet of overlying allivalite and, consequently when the Sgurr Dubh intrusion was subsequently uplifted it must have been in a relatively advanced stage of crystallization. Hutchison observed evidence of local shearing at the western contact of the Sgurr Dubh intrusion which he regarded as indicating that the emplacement of the ultrabasic rocks occurred under considerable stress. This evidence appears to be consistent with the hypothesis that the rocks were emplaced in a relatively crystalline state.

Weedon (1965, p. 61-66), however, considered that the Sgurr Dubh intrusion was formed in situ by gravitative accumulation of crystals from a basaltic or picritic magma, the cumulus phases in the lower part of the intrusion (dunites and peridotites) being olivine and spinel and those in the upper part (allivalites and felspathic peridotites) being olivine, spinel and plagioclase. He suggested that the large poikilitic "intercumulus" crystals of plagioclase were formed by a diffusion process analogous to that proposed by Hess (1939) for the Stillwater complex. Weedon (1965, p. 65) also observed evidence of relative movement of the Sgurr Dubh intrusion and the adjacent gabbros but, unlike Hutchison, he concluded that this movement must have been slight.

A third possibility is that the Sgurr Dubh intrusion, like the dykes, was emplaced as a magmatic suspension of olivine crystals. After emplacement the olivine crystals could have accumulated under the influence of gravity in a manner similar to that proposed by Weedon for crystals nucleating from a magma after intrusion. Such a mechanism would account for the general upward decrease in olivine content and, if the nucleation of plagioclase did not commence until the settling of the olivine crystals was comparatively advanced, it would also account for the absence of cumulus plagioclase from the lower part of the intrusion. If the Sgurr Dubh rocks were formed in this way, however, the banding in the lower part of the intrusion must be attributed to crystal sorting by magmatic currents rather than to rhythmic crystal nucleation as suggested by Weedon (1965, p. 64). In the upper part of the intrusion cumulus felspar evidently nucleated from the suspending liquid and would almost certainly have been accompanied by some crystallization of olivine (Osborn and Tait, 1952).

Before the relative merits of the above three hypotheses can be assessed, it is necessary to consider how compatible each is with the evidence presented by the dykes.

If the Sgurr Dubh intrusion represents the subsequently uplifted basal accumulate from the Layered Allivalite magma, and it was emplaced in a relatively crystalline state, it appears unlikely that the dykes could have been intruded as magmatic suspensions of olivine and spinel crystals contemporaneously with the Sgurr Dubh intrusion since the intercrystalline liquid of the accumulate would have crystallized before the suggested time of uplift (see above). It is evident from the radial distribution of the dykes that the point from which they diverged is in the centre of the Cuillins. The direction of flow in dyke 1 is inclined at approximately 25° to the horizontal (chapter XII.6) and, if this inclination is constant along the length of the dyke, it can be estimated that the point of divergence of the dykes is approximately 11,000 feet below the present sea level. Since, according to Zinovieff (1957) the Layered Allivalites are approximately 6,000 feet thick, this estimate suggests that the source of the dykes was too deep for them to have originated as a basal accumulate from the Layered Allivalites.

If the Sgurr Dubh intrusion was formed by crystallization and gravitative accumulation in situ, as proposed by Weedon, suspensions of cumulus olivine crystals without crystals of cumulus felspar would only have been available during the formation of the lower part of the intrusion. Since at any one time the thickness of the crystal mush formed in this manner would have been of the order of six feet (Hess, 1939; Weedon 1965, p. 62) this mush would have constituted an extremely limited source of suspensions of the type which formed the dykes. In addition, many of the dykes occur at similar altitudes to, or are lower than, the lower part of the Sgurr Dubh intrusion. This, together with the fact that the dykes flowed outward and upward, appears to preclude the possibility that the dykes were formed by the outward movement of suspensions of olivine crystals from the top of the crystal pile of the Sgurr Dubh intrusion during its accumulation in situ.

However, if the Sgurr Dubh intrusion was emplaced as a suspension of olivine crystals, the suspensions which formed the dykes could have been intruded approximately contemporaneously with this suspension from a common source located below the present level of the intrusions. Large poikilitic crystals of pyroxene and plagioclase frequently occur in the dykes. The crystals of pyroxene are unzoned and those of plagioclase generally exhibit only slight marginal zoning. Since it appears highly improbable that the diffusion mechanism favoured by Weedon for the Sgurr

Dubh intrusion could have operated in intrusions as small as the dykes, it seems that the pyroxene crystals and the unzoned cores of the plagioclase represent an equilibrium assemblage and that non-equilibrium conditions prevailed only during the final stages of crystallization. This is compatible with the other evidence that the dykes cooled relatively slowly and implies that the liquid from which the plagioclase and pyroxene crystallized was originally very rich in lime and magnesia. The existence of a similar liquid has already been demonstrated by Drever and Johnston (1966). If the intercrystalline liquid of the Sgurr Dubh intrusion was similar in composition it is unnecessary to invoke extensive diffusion to explain the existence of large unzoned plagioclase crystals and there is no need to account for the absence of substantial overlying late differentiates.

In the course of the above discussion it has been shown that much of the evidence is incompatible with the petrogenetic hypotheses proposed by Hutchison and Weedon and the writer believes that the Sgurr Dubh intrusion was, like the dykes, emplaced as a suspension of olivine crystals in an ultrabasic liquid, i.e. the third of the possibilities suggested above. The possible origins of magmatic suspensions of this type are considered below.

Concentrations of olivine crystals are generally regarded as having been formed by gravitative accumulation from a basaltic magma but it has been suggested that the intercrystalline liquid of the magmatic suspensions which formed the dykes (and the Sgurr Dubh intrusion) was ultrabasic and, consequently, no further consideration of this possibility is necessary. If the magma which gave rise to the Layered Allivalites represents an upper fraction drawn off after differentiation of the original magma at depth by gravitative settling of olivine crystals, the residual suspension of olivine crystals could have been subsequently intruded to form both the dykes and the Sgurr Dubh intrusion. However, this hypothesis (like that of basal accumulation below the Layered Allivalites discussed above) requires an almost total lack of crystallization of the intercrystalline liquid of the accumulate during the consolidation of several thousand feet of Layered Allivalite, and consequently, appears unlikely.

It is generally accepted that the mantle is peridotitic, at least in part, and partial fusion of this peridotitic material has frequently been proposed as a source of basaltic magma (Bowen, 1928, p. 315-320; Kushiro and Kuno, 1963; O'Hara, 1965). However, it appears to the writer that relatively little consideration has been given to the residual fraction of such partial fusion which might provide a possible source of suspensions of olivine crystals of the type involved in the formation of the dykes. If, during the partial fusion of peridotite, the early fractions were removed and further fusion of the residual material was insufficient to melt all the olivine and spinel, the residuum would consist of crystals of olivine and spinel in an ultrabasic liquid. The early fusion fractions could have been removed either once or periodically.

If the material which formed the dykes (and the Sgurr Dubh intrusion) was derived in this way, the Layered Allivalites could represent the last fraction to be drawn off and emplaced before the mobilization of the residuum, thus producing a relationship between the Layered Allivalites and the Sgurr Dubh rocks of the type suggested by Hutchison. Reay and Harris (1964) have demonstrated that, at atmospheric pressure, the earliest fractions from the partial fusion of peridotite are tholeiitic. If the same is true of partial fusion at higher pressures, it may be significant that there are abundant tholeiitic rocks (the Gars-bheinn Gabbro and the Outer Tholeiitic Complex) in the area which are earlier than the Layered Allivalites and could represent the earliest fractions of the partial fusion of a peridotitic source rock.

Translation lamellae are abundant in the olivine crystals in both the dykes and the Sgurr Dubh intrusion. Translation lamellae occur in many olivine-rich rocks and are particularly common in olivine nodules in basalts (Ross, Foster and Myers, 1954, p. 727-728; Hamilton, 1957, p. 137). Turner (1942, p. 281) regarded the lamellae as being "certainly of deformational origin" and Chudoba and Frechen (1950) concluded that they were caused by stress at elevated temperatures where the crystals were sufficiently plastic to translate. Hamilton, (1957, p. 138) suggested that lamellae might be formed by local shear during the closing stages of crystallization and Voll (1960, p. 512-513) regarded them as structures of tectonic origin. It is generally agreed, therefore, that translation lamellae are produced by the action of pressure on the olivine crystals. It is usually implied that the deformation took place while the olivine crystals were incorporated in a solid rock, but Phillips (1938, p. 134) considered that the lamellae could have been caused by "the stresses acting during the emplacement of an olivine-rich intrusive". It appears extremely unlikely however, that strong directed pressure could have been maintained on rotating, migrating olivine crystals suspended in a flowing magma, and it therefore seems improbable that the translation lamellae were formed during the intrusive flow of the dykes. If the translation lamellae were not formed during the intrusion of the dykes it appears reasonable to assume that the lamellate olivines were originally present in the suspension.

If the suspension of olivine crystals which formed the dykes originated at depth by the crystallization and gravitative accumulation of olivine crystals from a magma, the deformation could not have occurred while the crystals were suspended in this magma since directed pressure (as opposed to hydrostatic pressure) is required. The deformation could have occurred while the crystals were buried in the crystal mush but since the total thickness between the top of the crystal pile and the completely crystallized rock would only have been a few feet (Hess, 1939) it appears doubtful if sufficiently strong directed pressures could have arisen. If, however, most of the olivine did not crystallize from a magma but was derived by partial fusion of an olivine-bearing source rock, the translation lamellae could have been tectonically produced in the source rock and would be the only surviving evidence of the deformation of this rock. This deformation could have occurred long before the partial fusion or it could have been associated with orogenic activity which caused the fusion.

Chudoba and Frechen (1950) observed that in olivine-bearing rocks which they considered had been deformed in their present position the angles of displacement of adjacent lamellae were never more than 7° whereas those in the olivine nodules and inclusions in basalts were often as large as 11°. They concluded that this was due to the increased plasticity of the olivine crystals in the nodules which had been deformed at higher temperatures and therefore had originated at greater depth. Angles of more than 12° have been observed in the olivine crystals in the dykes and, if the conclusions of Chudoba and Frechen are valid, these olivine crystals must have been deformed under conditions similar to those under which the olivine crystals in the nodules in basalts were deformed. Since these nodules are regarded by many writers as representative of mantle material, this evidence is consistent with the hypothesis that the suspension from which the dykes were formed was derived by partial fusion of peridotitic mantle material.

It is tentatively suggested, therefore, that the dykes (and the Sgurr Dubh rocks) may have originated as the residual fraction of the partial fusion of a deep seated peridotitic rock and that the Layered Allivalites and Gars-bheinn Gabbro may represent the earlier fractions. It is also suggested that the emplacement of such a residual fraction occurred while the earlier fractions were still at an elevated temperature (although completely crystallized). This would account for the relatively low thermal gradient which apparently existed between most of the dykes and their host rocks. It is further suggested that the liquid with its suspended crystals flowed upwards through a single conduit until it reached the point from which it diverged to form the dykes and the Sgurr Dubh and An Sguman intrusions.

XVIII ORIGIN OF THE COGNATE XENOLITHS

The ultrabasic xenoliths in the dykes differ in several important respects from the olivine nodules commonly found in basalts and believed to have been derived from the upper mantle. Although occurring throughout the world, these olivine nodules are invariably composed of olivine, enstatite, chrome diopside and chrome spinel (Ross, Foster and Myers, 1954). The xenoliths in the dykes, on the other hand, although formed mainly of olivine and spinel, have not been observed to contain enstatite and they always contain plagioclase. In addition there is a much greater diversity of types among the xenoliths in the dykes than among the olivine nodules recorded from basalts. Consequently, although the dykes are believed to have been derived from a peridotitic rock which may have been part of the mantle, there seems little doubt that the xenoliths in them are not fragments of the upper mantle. Even if the peridotitic source rock was not part of the mantle, the absence of fusion or marginal corrosion of the xenoliths in the dykes (chapter XII.3) appears sufficient to preclude the possibility that they are relict fragments of this source rock.

Nevertheless, the mineralogical identity of the xenoliths with their host rocks suggests that the origin of the xenoliths is intimately connected with that of the dykes themselves.

In the layered ultrabasic rocks of south-west Rhum Wadsworth (1961, p. 49-53) observed local concentrations of ultrabasic xenoliths and suggested that these "igneous breccias" were the result of accumulation of "fragments of a previously consolidated part of the layered series" at the foot of a fault scarp. Ultrabasic xenoliths identical with those in the dykes occur in the Sgurr Dubh intrusion and have been attributed by Weedon (1965, p. 65) to autobrecciation. However, whereas most of the xenoliths in the Sgurr Dubh intrusion can be matched with rocks forming parts of the intrusion, those in the dykes are seldom similar to any part of the host dyke and it is evident that the ultrabasic xenoliths were introduced into the dykes. Only the xenoliths in a few of the highest dykes could possibly have come from the Sgurr Dubh intrusion and, consequently, this is a very unlikely source of the xenoliths in the dykes. Since there must therefore have been a source of ultrabasic xenoliths other than the Sgurr Dubh intrusion, it does not seem unlikely to the writer than the xenoliths in both the Sgurr Dubh intrusion and the dykes were introduced from a common external source. Such an origin would account for the presence of xenoliths in the highest levels of the intrusion and the features described by Weedon (1965, p. 65).

The range of rock types occurring as xenoliths and the presence of relatively abundant banded xenoliths suggest that the ultrabasic xenoliths were produced by mechanical disintegration of layered ultrabasic rocks similar to those occurring in the Sgurr Dubh intrusion. The only other indication of the origin of the xenoliths is the evidence (chapter XII.3) that they were incorporated in the magma for a relatively short time and, consequently, are believed to have originated comparatively close to the present position of the dykes.

Only a very tentative hypothesis concerning the origin of the cognate xenoliths can be advanced on the basis of the available evidence: this hypothesis is outlined below.

Prior to the intrusion of the dykes (and the Sgurr Dubh intrusion) part of the suspension of olivine crystals derived by partial fusion of the peridotitic source rock was mobilized and emplaced at a level below the point from which the dykes and the Sgurr Dubh intrusion diverged. The crystallization of this part of the suspension produced a small banded intrusion similar to that of Sgurr Dubh. During the consolidation of this intrusion no crystallization occurred in the liquid part of the main suspension of olivine crystals (which was still at the level at which the partial fusion occurred) and no further fusion occurred since the limit of fusion had already been reached. Subsequent intrusion of the main part of the suspension via the same conduit ruptured the small banded intrusion with the consequent incorporation of the fragments in the dykes and the Sgurr Dubh intrusion.

The above hypothesis is based on a number of assumptions for which no direct evidence is available but it does not seem inherently improbable and it is consistent with the observed dissemination of the xenoliths throughout the various intrusions and the short interval in both time and space between their incorporation in the magma and the crystallization of the "groundmass" minerals of the dykes.

XIX CONCLUSIONS.

The majority of the ultrabasic dykes investigated by the writer are of the Ben Cleat type. The dykes of this type were selected for detailed study and the principal conclusions of this research are summarized below.

The dykes are composed of olivine (Fa_{11}), clinopyroxene (Ca_{43} Mg_{46} Fe_{11}), plagioclase (An_{84} with normally zoned margins) and accessory chrome spinel. These minerals are invariably partly altered, mainly to antigorite, chlorite and magnetite, but the alteration is seldom extensive. The olivine crystals are either porphyritic or poikilitically enclosed by larger crystals of plagioclase or pyroxene. The pyroxene may be interstitial to the plagioclase but these two minerals are generally sub-ophitically intergrown.

The primary minerals vary in amount across individual dykes. The plagioclase : pyroxene ratios are relatively constant within each dyke and the amounts of these minerals are dependent on the olivine content which varies, often considerably, across the dykes. These variations are partly responsible for the differences in textures.

Five main types of olivine distribution have been recorded from the dykes. In all five there is a concentration of the olivine crystals towards the centre of the dyke, with either one or two maxima, and in two of the types there are also minor concentrations at the margins.

The average size of the olivine crystals also varies across the dykes. Increases in the average size generally correspond to increases in the olivine content but occasionally this relationship is reversed. Unlike the decreases in the sizes of the plagioclase and pyroxene crystals, which usually occur towards the edges of the dykes, the variations in the size of the olivine crystals cannot be attributed to the inward cooling of the dykes.

Although the dykes are transversely differentiated there are no cryptic mineralogical variations and the differentiation is therefore due entirely to the variation in the amounts of the primary minerals.

There seems to be little doubt that each of the dykes was emplaced as a single pulse and Bowen's (1928) hypothesis that the dykes were formed by composite intrusion is not therefore substantiated by the results of this investigation. It appears equally certain that the intruded material was a relatively concentrated suspension of olivine crystals in a lime-rich ultrabasic liquid. This material may have originated as the residuum from the partial fusion of a peridotitic rock, which may or may not have been part of the mantle. If it was derived from the mantle in this manner, the material must have moved upwards in bulk for a considerable distance before diverging to form the radiating group of dykes, since the point from which the dykes radiated appears to have been at a moderately shallow depth.

The differentiation of the dykes did not occur *in situ* but took place during their intrusion. Most of the dykes are almost vertical and the magmatic suspension of olivine crystals flowed outwards and upwards from the point of divergence. In the flowing dyke material there existed small transverse forces similar to those theoretically anticipated, and recorded from experimental systems. These forces caused the suspended olivine crystals to migrate towards the centres of the dykes thus effecting flowage differentiation of the dykes. The various types of olivine distribution are direct results of flowage differentiation under slightly different conditions. The minor concentrations at the margins of some of the dykes may be due to increases in viscosity on cooling which retarded or prevented the axial migration of the olivine crystals.

The migration of the olivine crystals was more effective for large crystals than small ones and variations in the average size of the olivine crystals across the dykes are also an effect of flowage differentiation. Where there is an inverse relationship between the average size and the amount of olivine crystals it appears to have been caused by the dyke material flowing in a non-vertical fissure.

In most of the dykes the plagioclase and pyroxene did not crystallize until flow had ceased and, consequently, their distributions were not affected directly by the flowage differentiation. Occasionally, however, the plagioclase began to crystallize in the margins of a dyke shortly before flow stopped and in such cases there is evidence of slight migration of the plagioclase crystals away from the edges of the dyke.

In addition to the variation in olivine content within individual dykes, different dykes contain different amounts of olivine. There appears to be a direct relationship between the width of a dyke and its olivine content and this can also be attributed to differentiation during flow.

All the observed phenomena can be adequately accounted for by flowage differentiation and it is therefore concluded that it was this process which operated, often very effectively, during the intrusion of the ultrabasic dykes of the Ben Cleat type in south-west Skye and imposed upon them their distinctive differentiation.

Much of the evidence points to the dykes having cooled relatively slowly and this may have been due to the country rock being at an elevated temperature when the dykes were intruded.

All the dykes contain cognate xenoliths and in many of the dykes these are abundant. There is a large range of different types of xenolith but they are all composed of the same minerals as their host dykes.

It appears improbable that the xenoliths originated in the dykes after intrusion and, consequently, they must have been suspended in the dyke material when it was intruded. It is tentatively suggested that the xenoliths are fragments of a small layered intrusion which was petrogenetically related to the dykes and was ruptured by the dyke material during the intrusion of the dykes.

The xenoliths are randomly distributed throughout the dykes but tend to be less numerous at the extreme edges of the dykes. There are preferred orientations of the longest axes of the xenoliths parallel to the directions of flow and these were evidently imparted during the intrusion of the dykes. The distribution of the xenoliths was not markedly affected by flowage differentiation and this appears to have been due to their relatively large size and the increase in the viscosity of the suspending medium imparted by its content of olivine crystals.

It is also concluded that the dykes were emplaced contemporaneously with the Sgurr Dubh intrusion and that, like the dykes, this intrusion was probably emplaced as a suspension of olivine crystals in an ultrabasic liquid.

XX. OTHER ULTRABASIC INTRUSIONS

1. INTRUSIONS OF THE COIRE LAGAN TYPE.

a) Sheet 26.

Sheet 26 is a part of the small intrusive complex near the summit of Sgurr Dearg (Fig. 10). Its north end lies just below the main Cuillin ridge and its south end forms this ridge (Fig. 113). The sheet is 55 inches thick and dips to the east at approximately 15°.

Fig. 113. Sheet 26 (viewed from the west).

It intrudes, and is chilled against, medium-grained gabbro of the Main Ridge Tholeiitic Complex. Apart from a 7½ inch thick basic dyke which cuts its north end and possibly a porphyritic dolerite dyke (Fig. 10), sheet 26 appears to be the latest member of the complex. At the bottom of the sheet a fine lamination parallel to the lower contact is visible on the weathered surface (Fig. 114).

Fig. 114. Basal lamination in sheet 26.

The lower and marginal parts of the sheet are olivine-rich but approximately 40 inches above the lower contact there is a sudden change to an upper, olivine-poor part, the junction between the two parts usually weathering out as a step (Fig. 115). The sheet can therefore be divided into four zones, namely (in ascending order), the lower chilled zone, the olivine-rich zone, the non-porphyritic zone and the upper chilled zone.

Fig. 115 - Junction between the lower (olivine-rich) and upper (olivine-poor) parts of sheet 26.

The lower chilled zone extends upward from the contact for approximately 1 inch. On a microscopic scale the contact is irregular and small fragments of gabbro occur throughout the lower chilled zone. The contact rock is composed of 22½% olivine phenocrysts up to 2 mm. long in a matrix of dark brown glass. The olivine phenocrysts increase in size and amount away from the contact and half an inch above the contact they may be as long as 5 mm. Approximately ¾ of an inch above the base of the sheet the groundmass is visibly microcrystalline and at the top of the lower chilled zone variolitic intergrowths of pyroxene and plagioclase can be discerned. Small plagioclase phenocrysts less than 0.3 mm long occur throughout this zone but are more abundant in the lower part and may be accidental xenocrysts. Veins about 0.25 mm thick transgress the lower chilled zone, occasionally swelling to patches several millimetres in diameter. These veins are composed of plagioclase laths and granular crystals of pyroxene and magnetite. They are noticeably coarser-grained than the glassy or microcrystalline groundmass of the lower chilled zone and appear to have been formed by the injection of magma from slightly higher in the sheet subsequent to the chilling of the lower contact. The chilled zone grades upward into the olivine-rich zone.

At the bottom of the olivine-rich zone the rock is composed of 35½% olivine phenocrysts in a variolitic groundmass of plagioclase laths and pale brown clinopyroxene with accessory chrome spinel and magnetite. The olivine crystals may be as long as 5 mm. The variolitic intergrowths have a radius of approximately 0.5 mm. There is an upward increase in the olivine content (Fig. 116; Table 29) until approximately 15 inches above the base of the sheet the rock contains 48% olivine. Above this the olivine content gradually decreases. At a height of 8 inches above the base of the sheet the variolitic intergrowths may be as large as 4 mm in diameter, but above this the growths become less perfect and the texture gradually changes to sub-variolitic. However, the size of the plagioclase crystals continues to increase until, at a height of approximately 34 inches above the base of the sheet they may be as long as 3 mm: higher up they decrease in size. The modal composition of the centre of the sheet is given in Table 30.

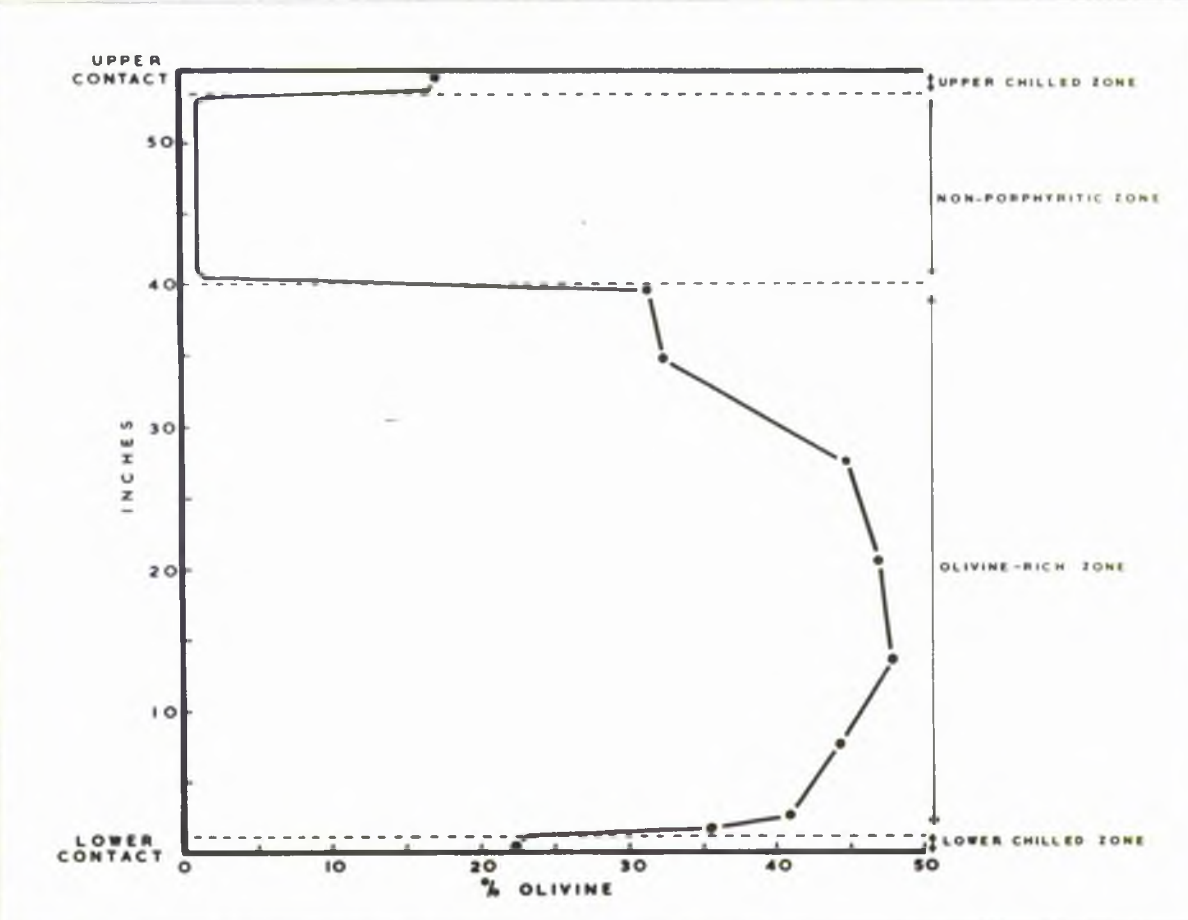

Fig. 116. Vertical variation in the olivine content of sheet 26.

Table 29

Olivine contents of specimens from sheet 26.

Height above base (inches)	% Olivine (including altered olivine)
¼	22.5
1½	35.5
2½	40.9
7½	44.3
13½	47.8
20½	46.8
27½	44.8
34½	32.3
39½	31.2
54¼	17.0

Table 30

Modal analysis of the rock 27½ inches above the base of the sheet.

Olivine	42.1%
Altered olivine (Mainly serpentine)	2.7%
Clinopyroxene	21.3%
Plagioclase	27.8%
Chrome spinel	1.7%
Chlorite	3.2%
Unidentified secondary minerals	1.3%

The compositions of the olivine and plagioclase have been determined optically. [Fewer determinations were made than on the corresponding minerals in the Ben Cleat dykes and consequently, the values are slightly less accurate.] The composition of the olivine is Fa_9 ($\pm$ 2% Fa) and that of the unzoned cores of the marginally zoned plagioclase laths is An_{83} ($\pm$ 2% An).

The lamination observed (above) on the weathered surface at the bottom of the olivine-rich zone is due to the long axes of the elongate olivine crystals being randomly orientated within a plane parallel to the base of the sheet, i.e. a planar parallelism of the tabular and prismatic crystals.

Above the junction of the olivine-rich zone with the non-porphyritic zone phenocrysts of olivine are rare and certainly form less than 1% of the rock. Throughout the non-porphyritic zone, however, small patches of a brownish secondary mineral, possibly bowlingite, are abundant and these may have been formed at the expense of small "groundmass" olivine crystals. If this is the case, it can be estimated that the rock may originally have contained as much as 5% "groundmass" olivine. Approximately coincident with the bottom of the non-porphyritic zone the texture changes from sub-variolitic to sub-ophitic. Throughout the non-porphyritic zone the grain-size of the rock gradually decreases upward until 1½ inches below the top of the sheet the rock becomes microcrystalline.

This microcrystalline rock and the reappearance of abundant olivine phenocrysts mark the bottom of the upper chilled zone. This zone is composed of approximately 17% small phenocrysts of olivine (often extensively altered to bowlingite and serpentine) and spinel in a groundmass of pyroxene and plagioclase which changes from microcrystalline to hyaline towards the upper contact of the sheet. The upper chilled zone differs from its lower counterpart mainly in the scarcity of small plagioclase phenocrysts, the smaller size of its olivine phenocrysts [the maximum length is less than 1.5 mm] and its slightly lower olivine content.

One specimen each of the olivine-rich zone, the non-porphyritic zone and the upper chilled zone have been chemically analysed and the results are presented in Table 31. The normative amounts of the minerals bear little resemblance to the modal amounts and this is due mainly to the altered nature of the rocks, particularly specimen (iii).

Table 31.

Analyses and norms of specimens from sheet 26.

Analyses (Wt %)	(i)	(ii)	(iii)	Norms (Wt %)	(i)	(ii)	(iii)
SiO_2	42.86	44.43	44.89	Qtz.	-	-	-
Al_2O_3	9.20	11.95	11.72	Or.	1.42	0.35	0.30
Fe_2O_3	2.57	3.87	6.53	Ab.	6.26	10.06	7.87
FeO	7.78	7.20	4.74	An.	21.07	27.09	27.66
MgO	24.53	16.63	15.25	Wo.	7.08	9.64	7.45
CaO	7.74	10.20	9.29	En.	5.38	7.20	6.16
Na_2O	0.74	1.19	0.93	Fs.	0.98	1.49	0.36
K_2O	0.24	0.06	0.05	En.	6.62	10.90	31.03
H_2O+	2.20	1.79	2.99	Fs.	1.20	2.25	1.84
H_2O-	0.22	0.13	1.10	Fo.	34.39	16.33	0.54
TiO_2	0.60	0.81	0.68	Fa.	6.87	3.72	0.04
CO_2	0.88	0.61	1.05	Mt.	3.73	5.61	9.47
P_2O_5	0.06	0.07	0.10	Il.	1.14	1.54	1.29
Cr_2O_3	0.24	0.52	0.12	Crt.	0.37	0.80	0.18
MnO	0.06	0.17	0.09	Ap.	0.14	0.17	0.24
	99.92	99.63	99.53				

(i) = Olivine-rich zone 13½ inches above the base of the sheet

(ii) = Non-porphyritic zone 52 inches above the base of the sheet

(iii) = Upper chilled zone.

Analyst :- F.G.F. Gibb.

The analysis of the specimen from the non-porphyritic zone (ii) indicates that this zone is rich in lime and relatively poor in alkalis and in this respect, therefore, it is essentially similar to the non-porphyritic zones recorded from other ultrabasic minor intrusions by Drever and Johnston (1958; 1966). The relationship between the normative olivine contents of the three analysed specimens corresponds closely to that between the modal olivine contents except that the normative olivine content of specimen (iii) is anomalously low. This, however, is undoubtedly due to the highly oxidised state of specimen (iii) which is reflected in the exceptionally high value for Fe_2O_3.

As in the Ben Cleat dykes, the olivine crystals frequently display translation lamellae and, hence, it appears probable that the sheet was emplaced as a suspension of olivine crystals in an ultrabasic liquid. However, large skeletal crystals are not uncommon and this suggests that some of the phenocrysts may have crystallized from the magma either during or after emplacement.

There seems little doubt that the quickly cooled upper and lower chilled margins represent the originally intruded material. Since these zones contain 17 and 22½% olivine respectively and the average olivine content of the sheet is approximately 32%, it seems reasonable to assume that the central part of the sheet must have contained more olivine crystals than the edges at the time of intrusion. In addition, the average size of the phenocrysts in the sheet is much greater than the average size in the margins.

Flowage differentiation in a sub-vertical feeder of the sheet or possibly in the gently dipping sheet itself (see chapter XI.3) could have produced a distribution of this type in which the olivine crystals increased gradually in size and amount from the top and bottom of the sheet towards the centre. The maximum concentration would probably have been below the true centre of the sheet due to the effect of gravity, which might also have been responsible for the slightly higher content of olivine phenocrysts in the lower chilled zone compared with the upper chilled zone.

However, if such a distribution of olivine crystals was effected by flowage differentiation, it appears that after flow ceased the olivine crystals (except those trapped in the chilled margins) settled out under the influence of gravity. It has been suggested by Bhattacharji (1965) that the settling rates of crystals decrease considerably with increases in their concentration. It is probable, therefore that the crystals above the maximum concentration established by flowage differentiation would have settled out relatively rapidly to produce the non-porphyritic zone while those near the maximum may have undergone relatively little settling before the suspending liquid crystallized.

It is therefore concluded that the present distribution of olivine in sheet 26 was caused by flowage differentiation during intrusion followed by the formation of the non-porphyritic zone by gravitative accumulation of the olivine crystals _in situ_.

b) Dyke 17.

Both outcrops of dyke 17 occur on the south flank of Sgurr nan Gobhar (Fig. 8). The dyke is a multiple intrusion, a 9 inch wide basic dyke being flanked by two 10 inch wide parts of an ultrabasic dyke against which it is chilled. The central member is a fine-grained olivine dolerite in which olivine occurs only as very small groundmass crystals. The ultrabasic member is readily distinguishable by its abundant olivine phenocrysts. Where it is in contact with the central member, the ultrabasic rock is composed of approximately 20% olivine phenocrysts, which may be as long as 1.5 mm, in a sub-ophitic groundmass of plagioclase laths and clinopyroxene crystals. The plagioclase laths have a maximum length of 1 mm. The ultrabasic member is chilled against the country rock and the decrease in the grain-size of the groundmass towards the contacts is accompanied by a decrease in the size and amount of olivine phenocrysts. The inward increase in the size and amount of the olivine phenocrysts in the earlier ultrabasic member indicates that flowage differentiation probably occurred during its intrusion.

One of the most noteworthy features of dyke 17 is the abundance, particularly towards the centre of the ultrabasic dyke, of lighter coloured, sub-spherical patches of rock up to 8 mm. in diameter. Examination of these patches in thin section reveals that they are composed mainly of plagioclase, pyroxene and secondary chlorite. The patches have sharply defined boundaries (Fig. 117) and are identical

Fig. 117. Olivine - poor sub-spherical patches in dyke 17. X 5; plane polarised light.

with the groundmass of the dyke apart from a relatively high content of secondary chlorite which is mainly responsible for their lighter colour. Olivine crystals are relatively rare in the patches although there is no decrease in the amount of groundmass or phenocrystic olivine in the vicinity of the patches. These patches appear to be similar to those recorded from the Igdlorssuit intrusion by Drever (1960) except that they do not contain substantial amounts of zeolitic minerals and lack peripheral veneers of magnetite.

Drever (1960) suggested that these spherical patches may represent immiscible liquid "globules" within the magma. Another possibility is that they are related to gas bubbles which accumulated in the magma.

c) Dykes 4, 5, 19, 22, 23, 24 and 25.

Dykes 4, 5, 19, 22, 23, 24 and 25 are all of the Coire Lagan type and, since dykes of this type have been extensively studied by Drever and Johnston (1958), only brief comments on each are given below.

Dyke 4, which occurs on the Elgol shore (Fig. 4), is composed of olivine phenocrysts in a sub-ophitic groundmass of plagioclase and pale brown clinopyroxene. Throughout the dyke the olivine crystals have a maximum length of 5 mm and examples displaying translation lamellae are abundant. In the central part of the dyke the crystals of plagioclase and pyroxene may be as long as 1.5 mm but they decrease in size towards the margins and the texture becomes sub-variolitic. The composition of the rock in the centre of the dyke is given in Table 32. The olivine phenocrysts decrease slightly in size and amount away from the centre of the dyke, again suggesting that some flowage differentiation has occurred.

Table 32

Modal analysis of a specimen from the centre of dyke 4.

Olivine + Serpentine	51.0%
Plagioclase	26.6%
Clinopyroxene	19.8%
Chrome spinel	2.2%
Secondary minerals	3.4%

Dyke 5 (Fig. 4) is formed of olivine phenocrysts with a maximum length of 3 mm in a variolitic groundmass of plagioclase and pyroxene. In the centre of the dyke the olivine is relatively unaltered and makes up almost half of the rock, but towards the margins it is increasingly altered to antigorite, chlorite and carbonate and at the margins it forms approximately one third of the rock. In the centre of the dyke the plagioclase crystals may be as long as 2 mm and are arranged in radiating growths. The plagioclase crystals are separated by thin veneers of clinopyroxene. These variolitic growths become smaller towards the edges of the dyke and near the contacts the groundmass is a dark brown glass chilled against the limestone country rock (Table 1). Approximately 4 feet away from the dyke the limestone is formed of colourless crystals of carbonate which may be very faintly clouded, whereas those in the limestone one inch from the dyke are very intensely clouded and have a dark grey colour. This can be attributed to thermal metamorphism of the limestone by the dyke magma.

Dyke 19 (Fig. 9) occurs on the main Cuillin ridge (chapter III.3). The only conspicuous feature seen in the field is a lamination parallel to the contacts which occurs throughout the dyke. A zeolitic mineral is extensively developed along the planes of fissility which are generally 1-2 inches apart. The rock is composed of phenocrysts of olivine (maximum length - 3 mm) and translucent brown spinel (maximum length = 0.3 mm) in a very fine-grained variolitic groundmass of plagioclase and pyroxene.

The olivine is extensively altered to serpentine and magnetite dust and the groundmass has a brown colour which is probably due to finely disseminated hematite. The dyke is chilled against the country rock.

Dykes 22, 23, 24 and 25 are members of the small complex south of the summit of Sgurr Dearg (Fig. 10). Dyke 22 varies in width between 3 and 5 feet. At one point on the north side of the main Cuillin ridge two tachylitic selvedges 1 foot apart can be observed running along the centre of the dyke. Examination of thin sections confirms that at this locality the dyke is a multiple intrusion but both members are almost identical, being composed of phenocrysts of olivine (maximum length 5.5 mm) and plagioclase (maximum length 2 mm) in a sub-ophitic groundmass of plagioclase and pyroxene which becomes finer-grained towards the outer margins of both members. Elsewhere the dyke appears to be a single intrusion.

Dyke 23 is composed of phenocrysts of olivine (maximum length = 3 mm), plagioclase (maximum length = 1.5 mm) and spinel (maximum length = 0.3 mm) in a very fine-grained sub-ophitic groundmass of acicular plagioclase crystals and clinopyroxene.

Dyke 24 is relatively poorly exposed and may be an independent dyke or a feeder of sheet 26. It is very similar to dyke 23 but the groundmass is coarser-grained and has a variolitic texture.

Dyke 25 is petrographically identical with dyke 22 except that plagioclase phenocrysts are virtually absent.

2. DYKE 7.

Dyke 7 is a one foot wide ultrabasic dyke which bisects outcrops 6/5 and 6/6 (frontispiece). It is chilled against dyke 6 with tachylitic selvedges more than $\frac{1}{4}$ inch thick. Inside each selvedge marginal zones approximately 2 inches wide are prominently displayed on the differentially weathered surface. These marginal zones are finer-grained than the central zone. A number of small offshoots from dyke 7 cut dyke 6. The largest of these (Fig. 118)

Fig. 118. - Offshoot from dyke 7.

is 5 feet long and tapers from $4\frac{1}{2}$ inches wide to less than 1 inch. The offshoots have tachylitic selvedges but do not show marginal zoning similar to that of the dyke. The dyke contains ultrabasic xenoliths but these are small and mainly confined to the central zone of the dyke.

Examination of dyke 7 in thin section confirms the existence of marginal zones within the chilled margins. The olivine content varies across the dyke and the marginal zones can be sub-divided mainly on the basis of their olivine content. The olivine distribution and the division of the dyke into zones and sub-zones parallel to the contacts are illustrated in Fig. 119.

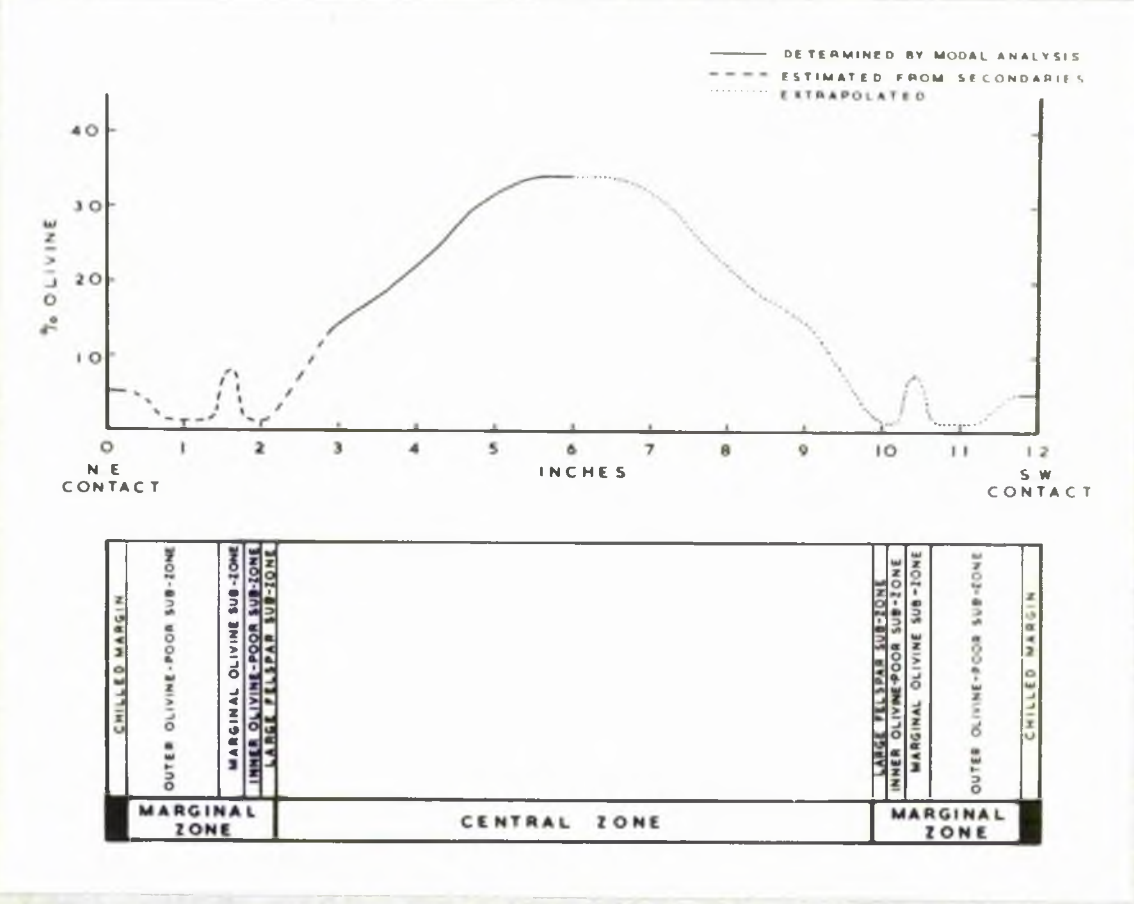

Fig. 119. Distribution of olivine across dyke 7 and the zonal division of the dyke.

Only one half of the dyke has been studied in detail but it is essentially symmetrical.

In the centre of the dyke the rock is composed of olivine phenocrysts with a maximum length of 3 mm in a sub-ophitic groundmass of plagioclase and pyroxene. The plagioclase laths may be as long as 0.75 mm. The composition of this rock is given in Table 33.

Table 33

Modal analysis of a specimen from the centre of dyke 7

Olivine	20.8%	33.8%
Altered olivine (Serpentine)	13.0%	
Plagioclase		32.4%
Clinopyroxene		23.6%
Chrome spinel		3.2%
Chlorite		7.0%

The olivine content decreases towards the edges of the dyke and half an inch from the edges of the central zone the olivine crystals are less than 1 mm long and form only 10% of the rock. In the half inch of the central zone immediately adjacent to the marginal zone the olivine crystals are extensively pseudomorphed by serpentine and the olivine content is difficult to assess. However the olivine content appears to continue to decrease gradually until at the edges of the central zone olivine and altered olivine forms less than 2% of the rock. At this point the maximum length of the plagioclase laths has decreased slightly to 0.5 mm.

The sharp junctions of the central zone with the marginal zones are marked by the development of plagioclase laths larger than those at the edges of the central zone. These laths may be as long as 3 mm and their long axes are sub-perpendicular to the junction between the two zones (Fig. 120). This is referred to as the large felspar sub-zone and it is approximately $\frac{1}{8}$ inch thick. Apart from the larger felspar crystals this sub-zone is composed mainly of small, randomly orientated plagioclase laths, sub-ophitically intergrown with clinopyroxene. Less than 2% of small olivine crystals are also present.

Next to the large felspar sub-zone is the inner olivine-poor sub-zone. It is approximately $\frac{1}{4}$ inch thick and, like the large felspar sub-zone, contains less than 2% fresh or pseudomorphed olivine crystals.

The inner olivine-poor sub-zone passes outwards into the marginal olivine sub-zone which is also $\frac{1}{4}$ inch thick. The only difference between the two is that the marginal olivine sub-zone contains between 5 and 8% of small olivine phenocrysts.

Between the marginal olivine sub-zone and the chilled margin is the outer olivine-poor sub-zone. This sub-zone varies in width from half an inch to 2 inches but it is usually $1\frac{1}{2}$ to $1\frac{3}{4}$ inches wide. It is identical with the inner olivine-poor sub-zone. Throughout the entire marginal zones the rock gradually becomes finer grained towards the contacts until $\frac{1}{4}$ inch from the contact the groundmass is microcrystalline and it becomes increasingly glassy towards the edges of the dyke. Towards the outer edges of the outer olivine-poor sub-zones small phenocrysts of olivine appear and these increase in number towards the chilled margins, which may contain as much as 5% olivine. The chilled contact of the dyke is not perfectly planar but undulates slightly. Apart from those between the chilled margins and the outer olivine-poor sub-zones, the zonal interfaces do not follow these minor undulations but remain parallel to the strike of the dyke (Fig. 120), the undulations being accommodated partly by the variations in the width of the outer olivine-poor sub-zone.

Fig. 120. Marginal zones in dyke 7.

The general olivine distribution in the dyke is typical of those attributed to flowage differentiation but the existence of large felspar and marginal olivine sub-zones appears to be anomalous. However, without a more detailed study of this dyke, the writer is unable to offer a satisfactory explanation of these anomalies.

3. DYKE 32.

Dyke 32 is a dark reddish-brown weathering dyke which occurs on the west side of Coire nan Laogh. It has an unusual lenticular form (Fig. 11) with a maximum width of approximately 14 feet. It contains abundant xenoliths of olivine eucrite (chapter IV) and is completely different from any of the other dykes investigated in this research.

The centre of the dyke is composed of phenocrysts of olivine and plagioclase in a very fine-grained groundmass of plagioclase laths and granular crystals of clinopyroxene and magnetite (Fig. 121).

The olivine phenocrysts may be as long as 3 mm and form approximately 21% of the rock. They invariably have a rim of secondary magnetite and are peripherally altered, mainly to serpentine, within this rim. Occasionally serpentine completely pseudomorphs the olivine crystals. The plagioclase phenocrysts may be as long as 2 mm but they form less than 55% of the rock.

Towards the edges of the dyke the groundmass becomes even finer-grained and the phenocrysts of olivine and plagioclase, although

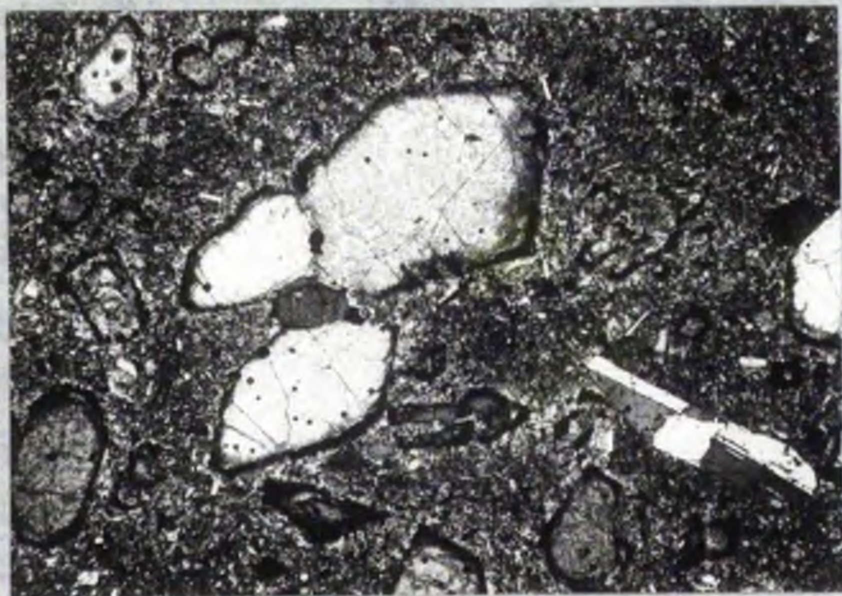

Fig. 121. Centre of dyke 32. X 15; crossed nicols.

as large as those in the centre of the dyke, are much less abundant. This unusual dyke has not been studied in detail as it appears most unlikely that it is closely related to the dykes of the type with which this research is principally concerned.

APPENDIX

MINOR INTRUSIONS OF THE STRATHAIRD PENINSULA.

1 INTRODUCTION.

During the search for ultrabasic dykes approximately 570 small dykes and sills were mapped in the Strathaird peninsula and the locations of these are given on Map 1. [The large basic sills intruded into the basaltic lavas in the Ben Cleat/Ben Meabost area and the large dolerite sill at Elgol (see Geological Survey 1"/mile map, sheet 71) have been omitted from the map. Dykes 1, 2 and 3 have also been omitted since a detailed map of these dykes has already been presented (Fig. 3).] Despite the large number of minor intrusions present in the area there appears to be a relatively limited number of different types.

Brief individual descriptions of the five ultrabasic dykes omitted from the main part of this thesis (chapter III.2) are given below along with short petrographical accounts of representative examples of the principal types of minor intrusion present in the area.

2 ULTRABASIC DYKES.

Altogether, ten ultrabasic dykes occur in the Strathaird peninsula. Five of these (dykes 1 - 5) have already been described. All five of the remaining dykes have chilled margins, are relatively narrow and appear to be free from ultrabasic xenoliths. Although exhibiting some variations in olivine content, grain-size and texture, they are all basically similar to dykes 4 and 5 and consequently, there seems little doubt that all five are of the Coire Lagan type (chapter III.2.).

Dyke S4 occurs on the west coast of the peninsula 900 yards south of Elgol (Map 1). The central part of the dyke is composed of approximately 25% olivine phenocrysts and less than 10% plagioclase phenocrysts in a very fine-grained groundmass of acicular plagioclase crystals sub-ophitically intergrown with clinopyroxene. The phenocrysts may be as long as 1 mm but the groundmass plagioclase crystals are less than 0.25 mm long. Translucent brown spinels, often with an opaque rim of magnetite, are common and the olivine phenocrysts are frequently altered to serpentine and chlorite.

Dyke S10 occurs on the east coast (Map 1). The central part of this dyke is formed of more than 50% olivine phenocrysts, which may be as long as 3 mm, in a very fine-grained groundmass of acicular plagioclase crystals (less than 0.25 mm long) sub-ophitically intergrown with pyroxene. From its location it could be a continuation of dyke 4, but petrographically, it differs markedly from dyke 4 (chapter XX.1.c). However, the differences are mainly in the texture and grain-size of the "groundmass" and, since these could be due to local variations in the conditions under which the dykes cooled, they cannot entirely preclude the possibility that dykes 4 and S10 are parts of the same intrusion.

Dyke S12 is the widest of the Coire Lagan type dykes, being more than 15 feet wide (cf. 11 feet for dyke 4). It is composed of more than 50% olivine phenocrysts, which may be as long as 4 mm, in a medium-grained sub-ophitic "groundmass" of pyroxene and plagioclase. The plagioclase crystals are either broad laths or sub-equant forms up to 2 mm long.

Dyke S28 is very similar to dyke 4. It is composed of approximately 50% olivine phenocrysts in a sub-variolitic "groundmass" of elongate plagioclase laths (maximum length = 2 mm) and clinopyroxene crystals. The main differences between this dyke and dyke 4 are that the olivine phenocrysts are smaller (maximum length = 2 mm) and the "groundmass" is slightly coarser-grained.

Dyke S47 is the central member of a three component multiple dyke on the west coast 525 yards north of the mouth of Allt Port na Cullaidh. It is composed of approximately 50% olivine phenocrysts (less than 3 mm long) in a sub-ophitic "groundmass" of clinopyroxene and broad plagioclase laths between 0.5 and 1.5 mm long. The principal differences between this dyke and dyke 4 are its lack of sub-variolitic texture and its slightly coarser "groundmass".

3. OTHER TYPES OF MINOR INTRUSION.

The majority of the minor intrusions of the Strathaird peninsula fall into one of the following types :- a) porphyritic olivine dolerite, b) olivine dolerite, c) plagiophyric dolerite and d) dolerite. Although much rarer, acid minor intrusions do occur and some of these are described in sub-section (e).

a) Porphyritic Olivine Dolerite.

Three sub-types have been observed and an example of each is briefly described below.

(i) Dyke S3 is composed of a few olivine phenocrysts less than 1 mm long in a very fine-grained groundmass of acicular plagioclase crystals sub-ophitically intergrown with clinopyroxene. The olivine phenocrysts are invariably partly or wholly replaced by an aggregate of talc and serpentine. Occasional plagioclase phenocrysts up to 1 mm long also occur.

(ii) Dyke S38 is very similar to S3 but contains no plagioclase phenocrysts and has a much higher olivine content. This dyke appears to be transitional between the porphyritic olivine dolerites and the ultrabasic dykes, particularly dyke S4.

(iii) Dyke S19 is a coarser-grained variety of olivine dolerite. The olivine phenocrysts may be as long as 2 mm and the "groundmass" is composed of sub-equant plagioclase crystals up to 2 mm long with subordinate interstitial clinopyroxene.

Some other porphyritic olivine dolerite dykes are :- S25, S27, S73.

b) Olivine Dolerite.

Dyke S5 is a typical olivine dolerite. It is composed of small subhedral and anhedral olivine crystals, very elongated laths of plagioclase less than 0.5 mm long and dark brown clinopyroxene. The felspar laths are sub-ophitically intergrown with the pyroxene.

Dykes S37 and S69 are two examples of dykes identical with dyke S5.

c) Plagiophyric Dolerite.

(i) Dyke S15 contains plagioclase phenocrysts up to 2 mm long which are set in a sub-ophitic "groundmass" of acicular plagioclase crystals (maximum length = 0.25 mm) and clinopyroxene.

(ii) Dyke S6 is very similar to S15 but the plagioclase phenocrysts are larger (maximum length = 5 mm) and the groundmass is even finer-grained, the acicular plagioclases having a maximum length of 0.1 mm.

(iii) Dyke S8 is composed of very large plagioclase phenocrysts, which are sometimes more than 1 cm long, in a sub-ophitic groundmass of plagioclase laths, approximately

0.5 mm long, and clinopyroxene. The groundmass is extensively altered to secondary minerals but there appears to have been originally a substantial amount of interstitial glass. Octahedra of magnetite are abundant. This dyke is coarser-grained than dyke S6.

The principal difference between the three sub-types is their grain-size and consequently, it appears possible that there is a continuous range of plagiophyric dolerites rather than a number of sub-types. Other plagiophyric dolerite intrusions in the area are S7, S9, S16, S24, S21, S26, S31, S33, S34, S36A, S54, S56, S71 and S75.

d) Dolerite.

The dolerite dykes and sills are composed essentially of plagioclase and clinopyroxene. They range from very fine-grained granular rocks, e.g. dyke S17B, in which minute acicular plagioclase crystals can just be discerned, to rocks in which the plagioclase laths are more than 1 mm long. In the finer-grained types the texture is sub-ophitic but in the coarser-grained varieties, e.g. dyke S17A, the pyroxene crystals may be as long as 2 mm and ophitically enclose the plagioclase crystals. Most of the dolerite dykes contain a small amount of interstitial glass but in some, e.g. dyke S76, this is completely absent. Minor amounts of olivine are present in some of the dolerite dykes in the form of very small crystals which are generally pseudomorphed by secondary minerals. Other dolerite intrusions in the area include S20, S22, S23A, S23B, S30 and S43.

e) Acidic Types.

Dykes of acidic rock occur in the peninsula but these are much less abundant than the basic dykes and sills. There appear to be two main varieties of acid dykes and an example of each is described below.

The first, e.g. S14, is composed of phenocrysts of felspar and amphibole in a medium/fine-grained groundmass of plagioclase, quartz, glass and iron oxide. The felspar phenocrysts are mainly of antiperthite and may be more than 5 mm long. The amphibole is a blueish-green pleochroic variety and is almost certainly hornblende. The crystals are small (less than 2 mm long) and may be replacements of pyroxene. The groundmass is composed of small laths of oligoclase (maximum length = 0.5 mm), frequently arranged in radiating clusters, and anhedral quartz crystals. The groundmass crystals invariably have a thin veneer of opaque material which may be glass or iron oxide. Secondary chlorite occurs, usually replacing the hornblende, and occasionally calcite partly replaces the felspar crystals.

The second variety, e.g. S29, differs from the first mainly in its finer grain-size and lack of ferromagnesian minerals. It is composed of phenocrysts of antiperthite less than 3 mm long in a fine-grained intergrowth of oligoclase and quartz. The felspar laths in the groundmass are less than 0.2 mm long and occasionally exhibit a slight parallelism. Magnetite and traces of apatite also occur in the groundmass.

Both varieties of acid rock are essentially similar to the rocks referred to by Harker (1904, p. 276-279) as quartz felsites, but in view of their distinctly porphyritic nature the term porphyritic quartz-felsite seems preferable.

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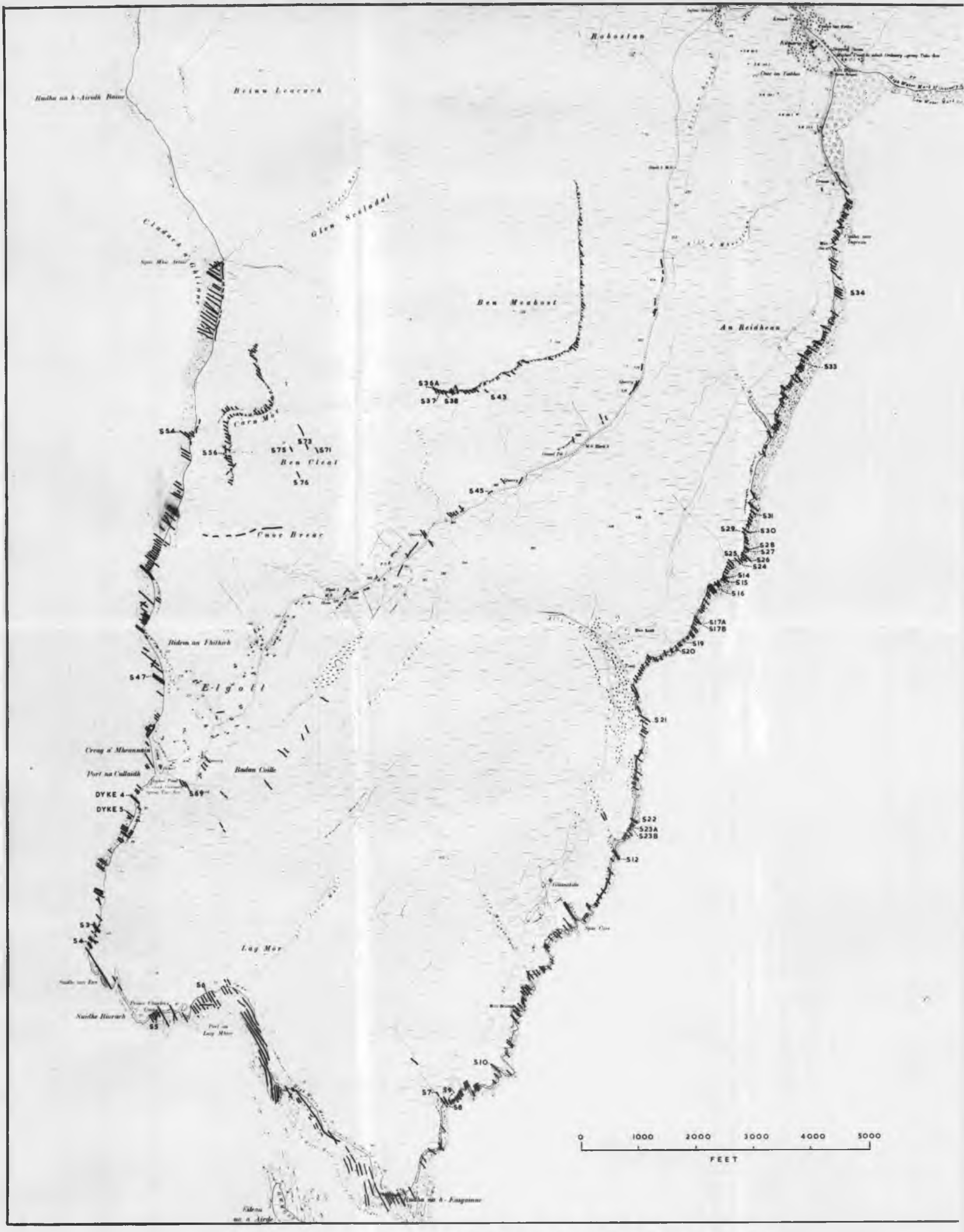

MAP I. – THE MINOR INTRUSIONS OF THE STRATHAIRD PENINSULA.

C U I L L I N
Coire a' Ghreadaidh
Coire na Banachdich
Coire Lagan
River Brittle
Glen Brittle
Loch an Fhir-bhallach
B R I T T L E
N
0
1000
2000
3000